NASA Contractor Report 165963

INTEGRATED APPLICATION OF ACTIVE CONTROLS (IAAC) TECHNOLOGY TO AN ADVANCED SUBSONIC TRANSPORT PROJECT–

ACT/CONTROL/GUIDANCE SYSTEM STUDY–VOLUME II, APPENDICES

FINAL REPORT

BOEING COMMERCIAL AIRPLANE COMPANY
P.O. BOX 3707, SEATTLE, WASHINGTON 98124

CONTRACT NAS1-15325
December 1982

[redacted]

~~Because of their possible commercial value, these data developed under Government contract NAS1-15325 are being disseminated within the United States in advance of general publication. These data may be duplicated and used by the recipient with the expressed limitations that the data will not be published nor will they be released to foreign parties without prior permission of The Boeing Company. Release of these data to other domestic parties by the recipient shall only be made subject to these limitations. The limitations contained in this legend will be considered void after December 1984. This legend shall be marked on any reproduction of these data in whole or in part.~~

NASA
National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

NASA Contractor Report 165963

INTEGRATED APPLICATION OF ACTIVE CONTROLS (IAAC) TECHNOLOGY TO AN ADVANCED SUBSONIC TRANSPORT PROJECT–

ACT/CONTROL/GUIDANCE SYSTEM STUDY–VOLUME II, APPENDICES

FINAL REPORT

BOEING COMMERCIAL AIRPLANE COMPANY
P.O. BOX 3707, SEATTLE, WASHINGTON 98124

CONTRACT NAS1-15325
December 1982

NASA
National Aeronautics and Space Administration

Langley Research Center
Hampton, Virginia 23665

X83-10066#

FOREWORD

This document constitutes the final report of the ACT/Control/Guidance System Definition Task of the Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project. The report covers work performed from December 1980 through January 1982 under Contract NAS1-15325.

Volume I contains the principal results of the study, and supplementary technical data are contained in Volume II.

The NASA Technical Monitor for this contract task was D. B. Middleton of the Energy Efficient Transport Project Office at Langley Research Center.

The work was accomplished within the Preliminary Design and Engineering Technology Departments of the Vice President—Engineering organization of Boeing Commercial Airplane Company. Key contractor personnel who contributed were:

G. W. Hanks	Program Manager
H. A. Shomber	IAAC Project Manager
A. F. Norwood	Preliminary Design Programs and Research Systems
L. W. Robinson	Task Manager
R. L. Erwin, Jr.	Air Traffic Control Analysis
J. H. Foster	Air Traffic Control Analysis
J. L. Groce	Air Traffic Control Analysis
J. G. Hatcher	Crew Systems Technology
J. M. Kraus	Crew Systems Technology
D. L. Parks	Crew Systems Technology
T. A. Pfaff	Crew Systems Technology
W. D. Smith	Crew Systems Technology
R. C. Wilcox	Crew Systems Technology
C. B. Crumb, Jr.	Flight Controls Design
W. F. Yee	Flight Controls Design
C. C. Flora	Flight Controls Technology
D. J. Maund	Flight Controls Technology
C. W. Erickson	Integrated Electronic Systems Technology

R. D. Force	Integrated Electronic Systems Technology
C. W. Lee	Integrated Electronic Systems Technology
D. G. Moss	Integrated Electronic Systems Technology
R. L. Norton	Integrated Electronic Systems Technology
K. C. Chan	Product Assurance
K.A.B. Macdonald	Product Assurance

During this study, principal measurements were made in U.S. customary units and were converted to Standard International units for this document.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

CONTENTS

Page

Page

Page

Page

FIGURES

Page

TABLES

SYMBOLS AND ABBREVIATIONS

GENERAL ABBREVIATIONS

ac	alternating current
alt	altitude
app.	appendix
AAL	angle-of-attack limiting
AAS	aircrew alert system
ACARS	ARINC communication addressing and reporting system
ACP	autoflight control panel
ACT	Active Controls Technology
AD	airspeed display
A/D	analog to digital
ADC	analog-to-digital converter
ADD	attitude director display
ADF	automatic direction finder
ADP	air data processor
ADS	air data sensor
ADSEL	address beacon surveillance system
AERA	automatic en route ATC
AFCS	automatic flight control system
AGL	above ground level
AHRS	attitude heading reference system
AIDS	airborne integrated data system
AIM	acknowledgment, ISO alphabet No. 5, and maintenance
ALCM	air-launched cruise missile
ALPG	autoland processor group
ALU	arithmetic logic unit
AOA	angle of attack
AP	attitude processor
APL	Applied Physics Laboratory
APU	auxiliary power unit
AR	antireflection
ARINC	Aeronautical Radio Incorporated

ARSR	air route surveillance radar
ARTCC	Air Route Traffic Control Center
ARTS	automated radar terminal system
ASCII	American standard code for information interchange
ASDE	airport surface detection equipment
ASR	airport surveillance radar
A/T	autothrottle
ATARS	automatic traffic advisory and resolution service
ATC	air traffic control
ATCRBS	air traffic control radar beacon system (ICAO term: SSR)
ATDP	air-turbine-driven pump
ATIS	automatic terminal information service
bps	bits per second
B	blue
BCAC	Boeing Commercial Airplane Company
BCAS	beacon collision avoidance system
BCD	binary-coded decimal
BITE	built-in test equipment
BMS	body motion sensor
cd	candela
cg	center of gravity
com	communications
C	Celsius
CAD	computer-aided design
CAS	computed airspeed
CAT I, II, III	ILS landing minimums
CCD	charge-coupled device
CCW	counterclockwise
CCZ	coastal confluence zone
CDMA	code-division multiple access
CDTI	cockpit display of traffic information
CDU	control display unit
CML	complementary merged logic
CMOS	complementary metal-oxide semiconductor
CNSP	communication and navigation status panel

CPU	central processing unit
CR	contrast ratio
CRT	cathode-ray tube
CSD	constant speed drive
CSMA	carrier-sense multiple access
CSPD	control surface position display
CW	clockwise
CWS	control wheel steering
CY	calendar year
dB	decibel
dc	direct current
DABS	discrete address beacon system (see Mode-S)
DATAC	Digital Autonomous Terminal Access Communication (System)
DCTTL	diode-coupled transistor-transistor logic
DH	decision height
DIGIVUE	trade name
DITS	Digital Information Transfer System
D/L	data link
DMA	direct memory access
DME	distance measuring equipment
DMOS	dielectrically isolated metal-oxide semiconductor
DOD	Department of Defense
DOT	Department of Transportation
DPG	dedicated pitch gyro
DRO	destructive readout
EAC	expected approach clearance
EADI	electronic attitude director indicator
EAROM	electrically alterable read-only memory
ECL	emitter-coupled logic
ED	engine display
EDP	engine-driven pump
EET	Energy Efficient Transport (Program)
EFL	emitter-follower logic
EGT	exhaust gas temperature
EH	electrohydraulic

EHSI	electronic horizontal situation indicator
E-JFET	enhanced junction field-effect transistor
EL	electroluminescence
EMA	electromechanical actuator
EPR	engine pressure ratio
EPROM	eraseable, programmable read-only memory
ES	engine sensor
ETA	estimated time of arrival
fc	footcandle
fig.	figure
fJ	femtojoule
fL	footlambert
4-D	four-dimensional navigation
F	Fahrenheit
FAA	Federal Aviation Administration
FAD	fuel advisory departure
FAPG	flight augmentation processor group
FAR	Federal Aviation Regulation
FDD	flight deck display
FDM	frequency-division multiplexing
FDMA	frequency-division multiple access
FE	flight engineer
FEA	Federal Energy Administration
FEPG	flight essential processor group
FET	field-effect transistor
FGPG	flight guidance processor group
FID	flight instrument display
FLIR	forward-looking infrared
FMC	flutter-mode control
FMPG	flight management processor group
FS	fuel sensor
g	acceleration due to gravity
G	billion; green
GaAs	gallium arsenide
GHz	gigahertz

GLA	gust-load alleviation
GMT	Greenwich mean time
GPS	global positioning system (formerly NAVSTAR)
GPWS	ground proximity warning system
GS	glide slope
G/S	ground speed
h	altitude
hp	horsepower
HDD	head-down display
HF	high frequency
HHUD	holographic head-up display
HMOS	high-performance metal-oxide semiconductor
HOL	higher order language
HSD	horizontal situation display
HSI	horizontal situation indicator
HUD	head-up display
inHg	conventional inch of mercury
IAAC	Integrated Application of Active Controls Technology to an Advanced Subsonic Transport Project
IAP	integrated actuator package
ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronic Engineers
IFR	instrument flight rule
I^2L	integrated injection logic
ILS	instrument landing system
IMC	instrument meteorological condition
INS	inertial navigation system
I/O	input/output
IR	infrared
IRS	inertial reference system
ISA	ICAO standard atmosphere
ISL	injection Schottky logic
ISO	International Standards Organization
JFET	junction field-effect transistor
kHz	kilohertz

kn	knot
kPa	kilopascal
kV	kilovolt
kW	kilowatt
K	thousand
KCAS	knots calibrated airspeed
KEAS	knots equivalent airspeed
lb/in^2	pounds per square inch
lm/W	lumen per watt
Loran-C	long-range navigation, type C
lx	lux
L	length
LAS	lateral/directional-augmented stability
LC	liquid crystal
LE	leading edge
LED	light-emitting diode
LOC	localizer
LRU	line replaceable unit
LSI	large-scale integration
LSIC	large-scale integrated circuit
LSTTL	low-power Schottky transistor-transistor logic
mbar	millibar
mil	mil
min	minute
Mode-S	new ICAO-standard selective-address ATCRBS mode (see DABS)
ms	millisecond
mW	milliwatt
μm	micrometer
μs	microsecond
μW	microwatt
M	Mach; million
MAC	mean aerodynamic chord
MB	marker beacon
MESFET	metal semiconductor field-effect transistor
MFD	multifunction display

MFK	multifunction keyboard
MFP	multifunction panel
MHz	megahertz
MIL-STD	military standard
MLC	maneuver-load control
MLS	microwave landing system
MLW	maximum landing weight
MNOS	metal-nitride-oxide semiconductor
MOS	metal-oxide semiconductor
MOSFET	metal-oxide semiconductor field-effect transistor
MPa	megapascal
M&S	metering and spacing
MSAW	minimum safe altitude warning
MSL	mean sea level
MSPP	mechanical servo power package
MTBF	mean time between failures
MTOGW	maximum takeoff gross weight
MZFW	maximum zero fuel weight
nm	nanometer
nmi	nautical mile
npn	negative-positive-negative
ns	nanosecond
N1	low-speed compressor RPM
N2	high-speed compressor RPM
N/A	not available
NAS	National Airspace System
NAV	navigation
NAVSTAR	(see GPS)
ND	navigation display
NDB	nondirectional beacon
NDRO	nondestructive readout
NMOS	negative metal-oxide semiconductor
NV	not volatile
Omega	very-low-frequency navigation system
O	orange

OEW	operating empty weight
pJ	picojoule
pnp	positive-negative-positive
ps	picosecond
PA	public address
PAR	precision approach radar
PAS	pitch-augmented stability
PBT	permeable-base transistor
PDME	precision distance measuring equipment
PFC	pilot flight control
PMOS	positive metal-oxide semiconductor
PROM	programmable read-only memory
PS	pneumatic sensor
PTA	planned time of arrival
q	body pitch rate
rad	radian
ref	reference
r/min	revolutions per minute
rms	root mean square
R	red
RALT	radio altimeter
RAM	random-access memory
RC	resistance times capacitance
RCA	company name
RFI	radiofrequency interference
RMD	radio magnetic display
RMI	radio magnetic indicator
RNAV	area navigation
ROM	read-only memory
RPM	revolutions per minute
RVR	runway visual range
RW	runway
RZ	return to zero
s	second (same as sec)
sec	second (same as s)

SD	system display
SDFL	Schottky diode FET logic
SELCAL	selective calling
Si	silicon
SID	standard instrument departure
SOCMOS	selective-oxidation CMOS
SOISMOS	silicon on insulated substrate MOS
SOS	silicon on sapphire
SPS	surface position sensor
SRAM	short-range attack missile
SSB	single sideband
SSD	system status display
SSR	secondary surveillance radar (U.S. term: ATCRBS)
STAR	standard terminal arrival route
STTL	Schottky transistor-transistor logic
SX	longitudinal distance from runway threshold (positive forward)
SY	lateral offset from runway centerline (positive right)
TACAN	tactical air navigation
TBD	to be determined
TCAS	Traffic Alert and Collision Avoidance System
TCD	time-critical display
TDM	time-division multiplexing
TDMA	time-division multiple access
T_D	propagation delay
TE	trailing edge
TED	transfer electronic device
TFEL	thin-film electroluminescence
TFT	thin-film technology
T-NAV	four-dimensional navigation (see 4-D)
TOD	top of descent
TOLD	takeoff and landing data
TR	transformer-rectifier
TSO	technical standard order
T_T	total air temperature
TTL	transistor-transistor logic

TV	television
u	incremental value of forward velocity
UHF	ultra high frequency
UV	ultraviolet
vol.	volume
V	volt; volatile
VAC	voice-activated control
VASI	visual approach slope indicator
VAX	vertical address extended (computer)
V_C	airspeed
VFR	visual flight rule
VHF	very high frequency
VHSIC	very-high-speed integrated circuit
VLF	very low frequency
VMC	visual meteorological condition
VMOS	V-groove metal-oxide semiconductor
VOR	very-high-frequency omnidirectional range
VORTAC	combined VOR and TACAN
VSD	vertical situation display
V_T	true airspeed
W	watt
WLA	wing-load alleviation
WMS	wing motion sensor
Wshld	windshield
XPOND	transponder
Y	yellow
$\ddot{z}$	body normal acceleration
ZnS	zinc sulfide
ZnS:Cu	copper-activated zinc sulfide
ZnS:Mn	manganese-activated zinc sulfide

SUBSCRIPTS RELATED TO VELOCITY V OR MACH NUMBER M

D	dive
e	equivalent airspeed
LO	liftoff
MO	maximum operating
REF	reference speed
S	stall
1	"go speed," committed on takeoff
2	1.1 times minimum controllable speed with engine out or 1.2 times stall speed

SYMBOLS

γ	flightpath angle
Δ	change in quantity
δ	control deflection angle
μ	micro
σ	sigma
ϕ	bank angle
ψ	yaw attitude

APPENDIX A: 1990s AVIONICS TECHNOLOGY ASSESSMENT

This appendix presents in detail the data contained in Section 5.0 of Volume I.

A.1.0 DATA COMMUNICATIONS

A.1.1 INTRODUCTION

Avionic and control system architectures of the 1990s will use highly distributed, modular architectures and will be implemented in higher order languages (HOL) on 32-bit micromainframe computers. The sensors, actuators, and displays will be built partly from smaller microcomputers. A key link in the systems will be the data communications among the mainframe microcomputers, sensors, actuators, and displays.

This section briefly discusses the basis for digital communications among distributed processing systems. It also describes two of the current systems that are specific to aircraft: the MIL-STD-1553B and the Aeronautical Radio Incorporated (ARINC) 429 data buses. Subsection A.1.4.2 describes a new data bus system—Digital Autonomous Terminal Access Communication (DATAC)—which has certain advantages over the other two systems. The DATAC bus is a strong contender for the 1990s avionics suite data communication system.

A.1.2 DIGITAL COMMUNICATIONS

The four basic functions of a data communication network are transmission, switching, storage, and control. Each of these functions and how they interact are briefly described.

Transmission coupling is implemented in the form of links or channels. The goal is to transmit information over the channels end to end via the interconnected switching centers. The links may consist of twisted wire, coaxial cable, fiber-optic cables, or other media. Electrical characteristics of the link include such items as conditioning, synchronization, regeneration, and frequency spectrum.

There are three classes of switching: space division, frequency division, and time division. Space-division switching uses separate physical paths, and these paths always exist for a

given switch condition. Most electronic systems today use space-division techniques. Frequency-division and time-division switching differ from space-division switching in that separate physical paths or circuits are not required for each data transmission. When the number of elements is reduced, the cost of the interconnection network decreases correspondingly.

Frequency-division switching, also known as frequency-division multiplexing (FDM), is applied in two major areas: carrier transmission systems and data multiplexers. Simultaneous transmissions are established in different frequency bands with a means at both ends for discriminating and recognizing the assigned frequencies. Time-division switching is also known as time-division multiplexing (TDM). It, like its frequency counterpart, has become common for carrier transmission systems and data multiplexing. The technique can accommodate large numbers of users, and all users share the same portion of the frequency spectrum in a time-dependent manner. All information in TDM is represented digitally to achieve the required time separation between channels and to drive the synchronization at both ends of the link.

The storage function refers to the requirement for buffering information as it passes through the data communication network. Because analog data must be sampled to be converted to digital form, questions of time delay are raised. In control applications, these time delays can become critical. A number of studies (refs A-1 and A-2) are being undertaken to understand the implications of these delays.

The fourth function, and the one that is dealt with in most detail here, is control. Some element or elements must decide who may transmit and when, and with what format. Without such prearranged control mechanisms, a chaotic situation would exist.

A.1.3 AIRPLANE INTERSYSTEM COMMUNICATIONS

Much of the material in this subsection results from another Boeing study (ref A-3).

Technology for the transfer of digital data on commercial airplanes has evolved in support of the airplane program objectives of high performance, low operating costs, and low production costs.

Factors to be considered when designing digital data buses include the data types to be transferred, interchangeability, redundancy, etc. The ARINC 429 and ARINC 453 Digital Information Transfer Systems (DITS) have been developed to meet these factors. Any new multiple-transmitter bus protocol developed must meet these elements and have the growth potential to satisfy the data interchange requirements of new systems that may be developed.

The present generation of commercial digital data buses (ARINC 429 and ARINC 453) is used to transfer several forms of data; for example:

- Binary-encoded parameter data
- Binary-coded decimal (BCD) data
- Discrete data
- Acknowledgment, ISO alphabet No. 5, and maintenance (AIM)—this data type used to transfer more than one word of data as a word group
- File data transfer

Future requirements for additional modes of data transfer may include one-time rapid transfer of large blocks of data for computer memory downloading or for background format to a cathode-ray tube (CRT) display unit.

To transfer the data, a protocol will be required that can handle repeated parameters with minimum delay and can transfer intermittent multiple-word, variable-length messages. The data must be transferred with a suitably low error rate that can be tolerated by the error control policy of the data utilization units.

A.1.3.1 DATA ROUTING

Two principal methods of data routing exist: labeling and addressing. Labeling is used on ARINC 429 systems, and addressing is used on MIL-STD-1553B systems.

The decision whether to label or address data blocks must be made early in the design of the data bus system. The decision has a great impact on the bus system and on development of the avionics architecture.

Word labeling has advantages for digital words containing parametric data. Two of the advantages of labeling include:

- A labeled word can be used by several receiver units.

- The transmitter in a labeled word system does not need a list of the data utilization units requiring each data word.

Word addressing has advantages when digital data are exchanged between two units with handshaking and acknowledgment of correct data transfer. Handshaking requires that the exchange be limited to the two participating units.

A.1.3.2 MULTIPLE-TRANSMITTER BUSES

Multiple-transmitter buses have the potential for reducing the number of buses on a commercial airplane and producing a more flexible system to permit system growth. If multiple-transmitter buses are used, then a protocol must be used to allocate the data bus resource to the sharing transmitters in some agreed-to way.

Existing ARINC 700-series avionics use single-transmitter, broadcast-mode digital data buses: ARINC 429 and ARINC 453. Each data word is labeled as to contents and broadcasts on the bus to all connected receivers. The receiver decodes each label, and a decision is made at the receiver if the data word is to be used.

The single-transmitter system leads to a proliferation of data buses. The multiple-transmitter data bus concept permits shared use of the transmission medium if a protocol is used to maintain orderly use of the bus by the transmitters. The transmitted words can be labeled for broadcast use or can be addressed to particular receivers. The multiple-transmitter buses have the advantages of:

- System flexibility: New transmitter units can be added or new parameters transferred, without adding new buses, if bus loading limits are not exceeded. If labeled data are used, all parameters are available to all receivers.

- The number of data buses on a commercial airplane can be significantly reduced; however, the problems of bus redundancy and isolation must be addressed.

Digital data from multiple transmitters can be transferred in several ways:

- Code-division multiple access (CDMA), in which the binary transmitters share the transmission medium simultaneously. The electrical characteristics of the transmission medium and transmitters determine the characteristics of the combined signal at the receiver.

- Frequency-division multiple access (FDMA), in which the transmitters are exclusively allocated a part of the frequency bandwidth of the data bus.

- Time-division multiple access (TDMA), in which transmitters are allocated exclusive use of the data bus for a period of time. The transmissions from a single transmitter are time discontinuous.

The CDMA protocol is not recommended for general use on commercial airplanes. The composite signal from several binary asynchronous transmitters is complex and has information contained in several amplitude levels. The design of receivers for the asynchronous multiple-transmitter case has not been investigated in detail but would be more complex than TDMA receivers.

The FDMA protocol has been used extensively, and the design of receivers to decode one transmitter output is well defined. However, if a receiver is to obtain data from several transmitters, complexity of the receiver filtering and decoding is increased. If an additional transmitter is added to the bus, each receiver requiring data from the new transmitter must be modified by the addition of filters and decoders. The FDMA protocol is not recommended for general commercial airplane use.

TDMA protocol requires that each transmitter include a means of time sequencing its transmissions to ensure that it does not collide with transmissions from other transmitters. The TDMA method places the system complexity at the transmitter. The TDMA receiver need be no more complex than a receiver designed for a single-transmitter, intermittent-service bus.

Two classes of TDMA protocol exist: contention TDMA and noncontention TDMA. With contention TDMA, the transmitters contend for time on the bus when each has a message to send. With noncontention TDMA protocol, each transmitter is allocated a time slot on a regular basis by polling or some other agreed-to means. A TDMA protocol is recommended for commercial airplane multiple-transmitter buses.

A.1.3.3 SYNCHRONOUS AND ASYNCHRONOUS SYSTEMS

In modern commercial airplanes, complex calculations are often required on raw data before the information can be transmitted in a usable form to the flightcrew or to a data utilization unit. In the ARINC 429 single-transmitter bus, whenever the processor has completed its data processing, the bus transmitter is "flagged" and the data are serially placed on the data bus. Data sent on the bus are current, and output timing is determined by the processor.

In a noncontention asynchronous system, transmission of data takes place solely at the command of the protocol logic. The term "asynchronous" implies that the calculation and the data bus frame time are not synchronous. The possibility exists that the microprocessor will not have completed its calculations when the data word is sent; either the last previously completed calculation could be retransmitted, or a word containing a "data not ready" flag could be output on the bus. If the last computed data are retransmitted, transmission of stale data becomes a problem that must be considered.

In a noncontention synchronous system, knowledge of the time of transmission is used to determine when the processor should begin its computations in order to be completed before transmission is scheduled. This technique can be used to reduce the data staleness problem. The method assumes that the calculation frame time is known and that the calculation frame can be initiated at a time where the result will be available for the next

data bus frame time access. This method may not be feasible if a microprocessor in a unit is performing several tasks. The programming and timing associated with the task scheduling, synchronous with the data bus frame, will increase the complexity of the unit.

In a contention-transmitter-initiated system, the processor sets a word-ready flag when the data are ready for transmission. The transmitter then will try to gain access to the bus at the earliest possible time. Because of the contention protocol, a delay is involved in sending the data onto the bus. The delay will depend on the protocol used and the bus loading. For example, if the bus is free, then the data may be transferred with zero protocol delay. If the bus is busy, then transmission is delayed and access must be obtained in contention with other transmitters possibly waiting for service.

Single-transmitter buses, contention protocols, and asynchronous noncontention protocols are relatively easy to interface with a distributed processing system, as the microprocessor unit can run asynchronously with the data bus. This is particularly valuable if a microprocessor is performing several tasks.

For example, in the ARINC 429 single-transmitter data bus, whenever the transmitter has a word to send on the bus, it is transmitted immediately. In the contention protocol, when a transmitter receives a word from the microprocessor unit it waits until the bus is free and then begins transmission. A drawback with the asynchronous noncontention bus is that delays that are equally probable between zero and one frame time can be encountered from the time the calculations are completed to the time when transmission of the information occurs. The possibility of stale data must be addressed by the system designer.

To improve delay characteristics of the asynchronous noncontention buses, the processors can be made to operate synchronously with the controlling protocol. This significantly reduces the problem of stale data because the calculation is started at the correct time so that the information is ready to transmit just before the unit's transmission slot occurs. However, task scheduling problems exist with the synchronous data generation scheme.

A.1.4 COMPARISON OF CURRENT AND FUTURE STANDARDS FOR AIRPLANE DIGITAL TRANSMISSION SYSTEMS

A.1.4.1 CURRENT STANDARDS

The current standards for airplane intersystem digital transmission media are the military standard (MIL-STD-1553B) and the commercial transport standard (ARINC 429). A third standard (ARINC 453) is designed specifically for digitized transmission of weather radar video and will not be discussed.

A.1.4.1.1 MIL-STD-1553B

MIL-STD-1553B defines a high-speed, bidirectional transmission medium that has a low error rate and uses a twisted, shielded pair of conductors. Up to 31 terminals, each with the capability to be connected to a number of sensors and instruments, can be connected to the data bus. The military standard protocol differs from many other connection protocols in that all address data, command data, and information are carried in serial format on a single data bus. A designated bus controller terminal directs data traffic on the bus. The military standard allows this controller function to be independent or colocated with other terminals on the bus. The latest version of the standard provides dynamic reassignment of the bus control function.

Signals on the bus are composed of address and command, data, and status words. Each word is 20 bits long and is transmitted in a serial, digital, Manchester II biphase format at a bit rate of 1 MHz. The first 3-bit time period is called the synchronizing field and is followed by 16 information bits and then the last, or 20th bit, which is the parity bit.

The bus controller issues command words, containing the address of the terminal commanded, to listen to data on the bus or to transmit data on the bus. The types of information exchange are (1) controller to terminal, (2) terminal to controller, (3) terminal to terminal, and (4) broadcast. The signals of the first three types of transmissions are composed of command status words and blocks of up to 32 data words, while in the fourth type, or broadcast, the controller issues a 20-bit receive command word to specific addresses and follows with a block of up to 32 data words. Only properly equipped terminals can recognize broadcast commands and receive the data.

The MIL-STD-1553B is a very sophisticated data transmission network and, with its distributed control capability, can provide a high degree of reliability and adaptiveness to avionic systems.

A.1.4.1.2 ARINC 429

The ARINC 429 data transmission system consists of one pair of conductors (either shielded or unshielded), and data transfer is unidirectional from data source to data receiver. Each data word is encoded in binary or binary-coded decimal. The data words are composed of 32 bits, including parity. Files with 127 records or less may be transferred. Each record can have as many as 126 data words. When an odd parity check detects an error, no procedure is provided for correction and repeat transmissions are not considered. Synchronization is achieved by gap width, where a minimum gap width of four bit widths precedes the beginning of a new word. Two data rates are available, the high-speed 100K bps and the low-speed operation, which is within the range of 12K to 14K bps.

A.1.4.2 FUTURE STANDARDS

The Digital Autonomous Terminal Access Communication (DATAC) current mode data bus system (ref A-4) is based on two novel concepts: the DATAC protocol, which regulates data traffic on a single-channel medium, and the current mode bus medium, characterized by installation flexibility and benign failure modes.

A data communication system using DATAC protocol has the following basic characteristics:

- Any practical number of autonomous terminals is allowed.
- All terminals are identical.
- All messages contain unambiguous data identification.
- Transmissions from a given terminal are of constant duration and occur periodically.
- Transmission intervals are nominally the same for all terminals on the same bus.

- Transmissions may have any planned information format provided that gaps during these transmissions are of shorter duration than those gaps separating the transmissions from different terminals.

- Total duration of transmissions and gaps for all terminals on a bus must be less than the transmission interval for that bus.

- The transmission gap (i.e., the period of silence preceding any transmission of a given terminal) must be unique to that terminal.

The following protocol must be obeyed by all participating terminals:

- A terminal is in the receive mode, except when it is in the transmit mode.

- Terminal (i) transmits when the following conditions are satisfied:

  - Transmission interval T (duration since the beginning of the previous transmission by terminal (i)) has expired.

  - Transmission gap (g) has expired and the bus is still available.

Note that $T1 = T2 = T3 \ldots = Tn$ and $g1 < g2 < g3 \ldots < gn$.

The DATAC protocols can be characterized as carrier-sense multiple access (CSMA), noncontention, and autonomous. Two protocols, A-mode and B-mode, have been developed for DATAC. Both A- and B-mode protocols are simple in concept and display adequate behavior even in the presence of bus overload resulting from a planning error. The carrier-sense feature provides the basic stimulus to the transmission-delay mechanism. Each mode has two such mechanisms: one for clash-free priority resolution and the other for voluntary transmission deferral. For both modes, each terminal has a resettable gap timer, programmable by pin selection to a unique gap time for priority resolution. Absence of a carrier starts the gap timer, whereas presence of a carrier sets it back to zero. A terminal in which the gap timer has reached its modulo can start transmission, provided the voluntary deferral mechanism has also been satisfied.

The difference between the A- and B-mode operation is in this deferral scheme. In the A-mode, a transmission interval timer programmable by pin selection (and set to the same transmission interval in all terminals of a system) starts counting at the outset of a transmission by its terminal. The transmission interval is of sufficient duration to give all terminals in a system a chance to transmit their messages and still leave some growth capacity on the bus. An A-mode terminal will start a transmission only if both the gap timer and the transmission interval timer have run out. By definition, no other terminal is ready, at that instant, to start its transmission; priority has been resolved without clash.

In the B-mode, the deferral mechanism takes the form of a second gap timer. Again, it is programmable by pin selection and set to the same value in terminals of a system. The duration of carrier absence it measures is called "sync gap." The sync gap is longer than any of the unique transmission gaps. Only after the sync gap timer has run out will the transmission gap timers be allowed to start counting. Enforcing this sequence guarantees each terminal in the system a turn to access the bus.

A-mode operation is characterized by periodic transmission by each terminal in the system. Message duration of a given terminal is constant but can differ widely among terminals. Message scheduling is performed by the terminal on the basis of entries in its "personality" eraseable, programmable read-only memory (EPROM). The scheme allows selection of individual update intervals for different parameters as integer multiples of a transmission interval.

B-mode operation allows terminal message durations to change continually. This scheme provides clash-free priority resolution and guarantees each terminal access to the bus but does not maintain any particular rhythm. Because there is no message duration constraint, this mode is slightly more efficient than the A-mode.

Subsystem interface operation can also be controlled by the DATAC terminal, again on the basis of entries in the personality EPROMs. For simple subsystems, such as sensors, actuators, etc., no other processing capability will be needed for data routing. At the other extreme, a real-time computation in a microprocessor-equipped line replaceable unit (LRU) can be served by a DATAC terminal through a shared random-access memory (RAM), through the processor direct memory access (DMA), or by an interrupt procedure.

A.1.4.3 DATAC, ARINC 429, AND MIL-STD-1553B SYSTEM COMPARISONS

Figure 3 (vol. I) illustrates the installation configuration of the three candidate systems: the commercial standard, ARINC 429; the military standard, MIL-STD-1553B; and the proposed DATAC system. Figure 3 shows a rudimentary system configuration consisting of three remote devices, each requiring a number of data inputs from the other two units. The ARINC 429 system, using a separate bus for each of the data sources, would appear to provide the highest degree of independence because it is not limited to one single-channel medium. Hardware complexity is the penalty. An individual receiver needs to be provided in each unit for each data source.

The MIL-STD-1553B system is based on the idea that one of the terminals functions as a bus controller. System autonomy achieved with this approach is poor because all participating units depend on the fault-free operation of the central bus controller.

The system autonomy achieved by the DATAC system approaches that of the ARINC 429 standard, in that any of the participating systems can use the data bus regardless of the operational status of any of the other systems. Furthermore, many changes in the communication requirements of a given system can be made without any effect on the programming or operation of other systems in a DATAC network.

In steady-state operation, lack of absolute autonomy is caused by the minor frames of the communication sequences of the participating systems being synchronized (ordinarily no disadvantage) and also in the existence of certain central failure modes.

Of primary concern in a data bus system are central failure modes; i.e., faults capable of rendering the complete communication system inoperative. Terminal failures affecting only the unit served are considered, along with other unit faults, in determining unit reliability. Of somewhat greater concern are terminal faults affecting one or more unrelated units in addition to the unit served.

The following problems are typical in this group:

- Bus controller failure
- Active terminal failure

- Passive terminal failure
- T-coupler failure
- Bus medium failure

Of the three candidate approaches, only the MIL-STD-1553B system is subject to all listed potential failure modes. Also, unique to MIL-STD-1553B is the single most likely failure mode—a fault in the bus controller. An active terminal failure is one characterized by a faulty transmission, either because it is in violation of any of the protocol aspects, or any part of the message is incorrect, or the terminal is imparting signals onto the bus in violation of prescribed signal characteristics. Faults of this category may affect the unit served by the faulty terminal, terminals receiving data from the faulty terminal, unrelated terminals, or all participating terminals (central failure).

A passive terminal failure (i.e., loss of capability to transmit) affects all terminals receiving data from that data source. T-coupler failures, or failures of the T-connection between the terminal and the bus, along with bus medium failures, are dependent on bus implementation; i.e., current or voltage mode bus media.

Table A-1 summarizes failure susceptibility and likelihood of occurrence of a given type of failure for the three systems.

The DATAC approach is the least expensive to implement because it neither requires the large number of bus wires and receiver circuits needed in the ARINC 429 system nor does it involve a bus controller with its associated hardware and software.

A.1.5 CURRENT MODE DATA BUS

The multiple-transmitter data bus is a key element in many new-technology flight control and avionic system architectures being investigated because it helps eliminate much system-bound signal wiring and conveniently provides information needed for system monitoring or maintenance.

These features would be of questionable benefit if use of a bus would either compromise reliability of an individual system (or worse, all participating systems collectively), or if hardware or software control were to become unmanageable.

Table A-1. Bus Terminal Failure Modes and Effects

May affect Type of failure	Own unit	Related units	Unrelated units	Total system
Bus controller	Not applicable	Not applicable	Not applicable	Not applicable
Transmitter active				
Transmitter passive				

(a) ARINC 429

May affect Type of failure	Own unit	Related units	Unrelated units	Total system
Bus controller				
Transmitter active				
Transmitter passive				

(b) MIL-STD-1553B

May affect Type of failure	Own unit	Related units	Unrelated units	Total system
Bus controller	Not applicable	Not applicable	Not applicable	Not applicable
Transmitter active				
Transmitter passive				

(c) DATAC

Extremely improbable   Improbable   Probable   No effect

The current mode data bus (ref A-5) is a serial, digital communication medium that combines high reliability with ultimate configuration flexibility. The current mode data bus is excited, and signals on the line are sensed by ferrite cores. Transformers are formed by inserting turns of the twisted-pair wire onto the cores. Split cores are used so that they can be inserted without cutting the line, thus maintaining integrity of the main bus.

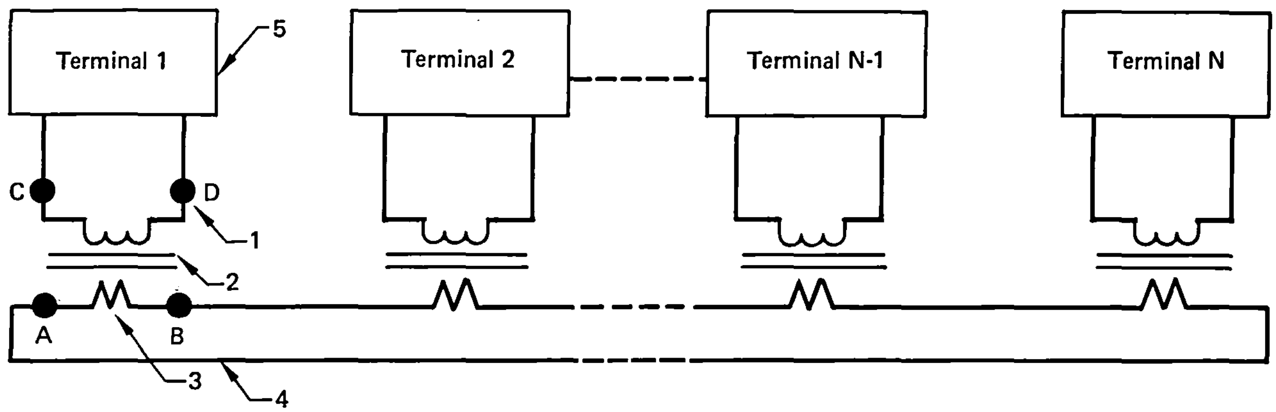
The line can be operated to above 1 MHz. The rapid increase of resistance with frequency, the increase in core loss with frequency, and the decrease in permeability limit the high-frequency response. Saturation of the cores can limit the low-frequency response.

Successful operation of the main bus can be maintained even with multiple failures of cores or windings. Because split cores are used, the line is never cut. Conductive connections are needed only on the ends to properly terminate the line. Three or four parallel resistors chosen to give the proper net resistance could be used. The successful operation of a 93m (300-ft) line, even at 1 MHz, is not sensitive to the value of the terminating resistance. Thus, if one of the four terminating resistors should open, the bus would still be operable at a slightly reduced current level.

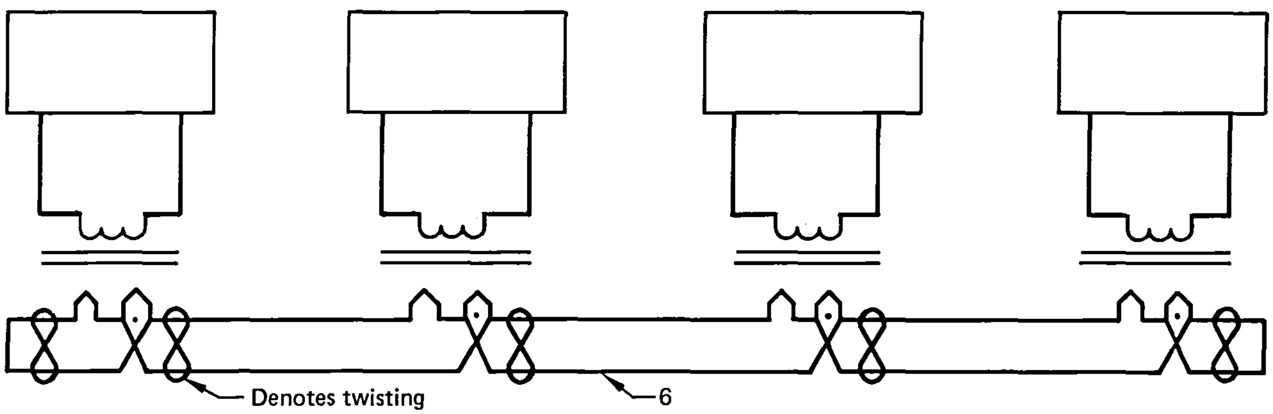
Opening a secondary winding (with no loaded tertiary winding on the transformer) does impair operation of the system. One, two, or three such failures could probably be tolerated. However, this problem can be minimized by adding a tertiary winding and loading the winding at the core.

A.1.5.1 DESCRIPTION OF THE CURRENT MODE DATA BUS MEDIUM

Figure A-1(a) (ref A-4) is a simplified electrical equivalent of the current mode data bus. It shows a number of terminal circuits (5), each coupled to the current loop (4) by means of a transformer consisting of the terminal winding (1), the transformer core (2), and the bus winding (3). Assuming that terminal 1 is in the transmit mode and terminals 2 through N are in the receive mode, an ac signal applied to the terminal winding of terminal 1 would then induce a voltage in the bus winding of terminal 1. This causes an alternating current to flow in the current loop (4). With similar parameters in all coupling transformers, it is then obvious that signals of similar wave shapes will be generated at the terminal windings of all receiving terminals.



(a) Electrical Equivalent, Simplified



(b) Electrical Equivalent

Figure A-1. Current Mode Data Bus

Figure A-1(b) constitutes a more accurate electrical equivalent of the current mode data bus. In particular, it shows that the data bus (6) is really a twisted-wire pair with short-circuit terminations and that both wires of this pair participate in every coupler by constituting one turn each of the bus winding.

Figure A-2 illustrates an initial physical arrangement using ferrite core halves (7) with a lapped interface (E). This figure shows that a coupler built in this manner can be easily inserted at any place along the wire bus (6) into two consecutive "loops" formed by the twisted-wire pair. Physical means of support, clasps to hold the core halves in magnetic contact, twisted, shielded wires connecting the terminal winding with the terminal electronics, and protective potting are recommended but are not shown in the figure.

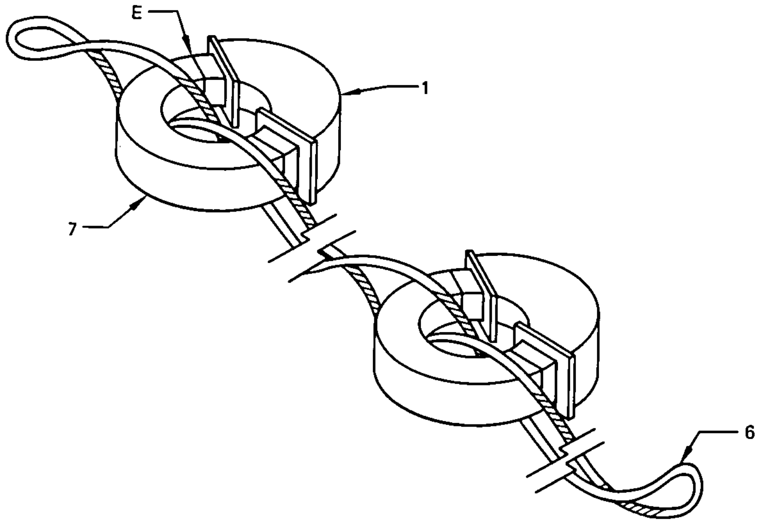


Figure A-2. Current Mode Data Bus Physical Arrangement

Figure A-3(a) is a U-I core implementation taking advantage of readily available hardware. The E-E core version, shown in Figure A-3(b), is possibly the easiest to insert into the bus medium. It operates with only one equivalent turn of the bus winding. Larger E-cores can be envisioned, threaded so that the bus winding has three equivalent turns.

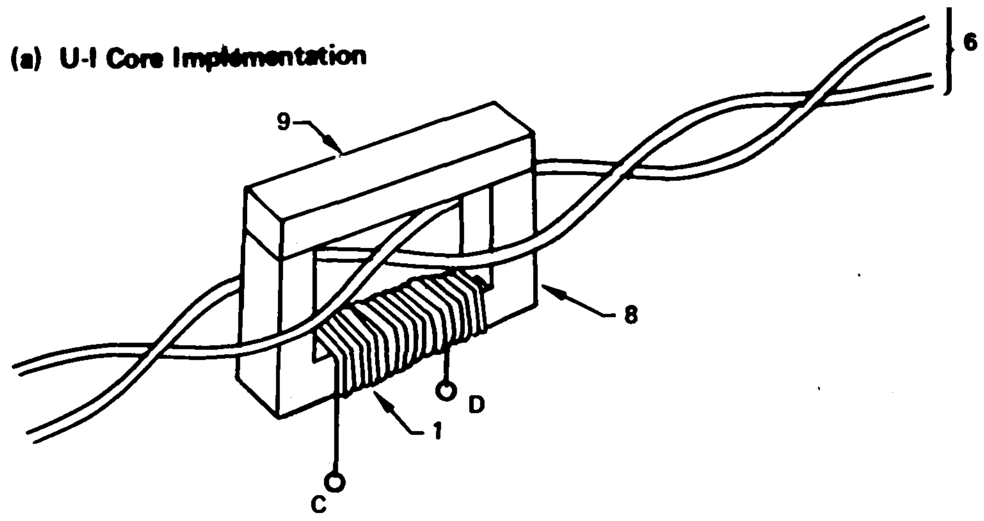
A.1.5.2 OPERATIONAL CHARACTERISTICS

The following current mode data bus characteristics satisfy the performance requirements listed previously for data buses in general:

- The bus medium consists of a twisted-wire pair of substantial wire strength with thick, high-voltage and abrasion-resistant insulation, and with a simple short-circuit splice at each end. Because no galvanic connections ever have to be made to the conductor of this bus medium, extreme reliability claims can be made for this element.

- Operation of the bus medium is insensitive to the operational status of any of the participating terminals.

- The bus medium, couplers, and stubs can be manufactured of simple, robust, passive components virtually unaffected by typical operating temperatures, air densities, and humidity levels.



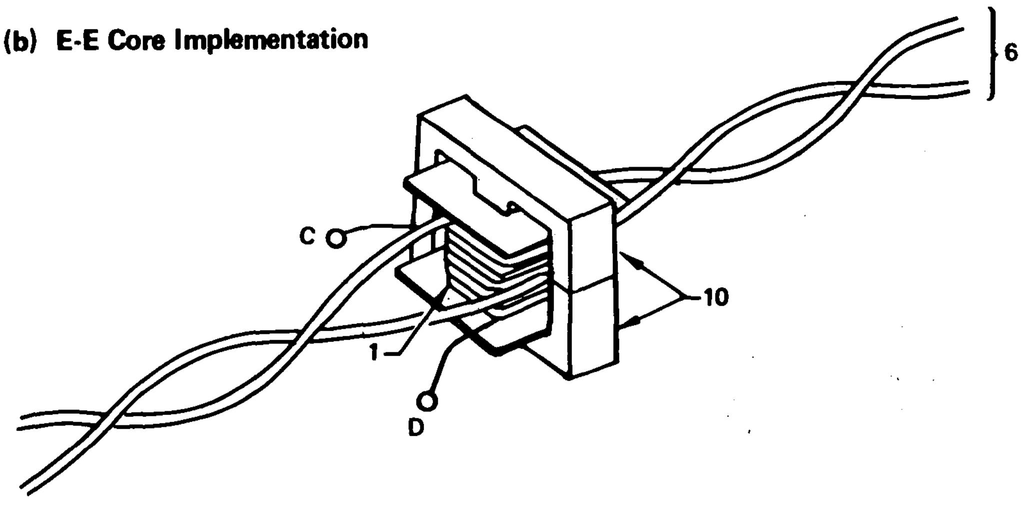


Figure A-3. Current Mode Data Bus Coupler Implementation

- Electromagnetic compatibility characteristics of bus, coupler, and stubs and the capability to withstand lightning strikes are very favorable:

  - Balanced-wire pair, electrically floating

  - No current paths to ground; hence, no potential to convert common mode voltages into differential ones

  - Uninterrupted high-voltage insulation over the full length of bus medium; couplers and stubs protected by shielding, with shielding grounded at the terminal end of the stub

A.1.5.3 COMPARISON OF CURRENT MODE AND VOLTAGE MODE BUS MEDIA

The two bus media are compared here considering an application that poses moderate data rate requirements, but where stringent cost, reliability, and flexibility goals must be met.

A.1.5.3.1 Bus Configuration

Figure 3 (vol. I) shows that the current mode bus medium can be used with the DATAC system, allowing a simple installation layout in an airplane. This system affords ultimate configuration flexibility, especially when used with DATAC protocol. Such flexibility is needed for customizing the avionics suite and for system-retrofitting additions or substitutions. These types of modifications in a voltage mode medium pose problems, because imperfections in splicing or connector installation may result in central medium failure.

A.1.5.3.2 Failure Modes

Table A-2 summarizes bus coupler and transmitter fault susceptibilities for the voltage mode and the current mode media. With respect to electrical fault propagation, a clear advantage is visible for the current mode system over the voltage mode system. This advantage is explained by the following principles:

- A short circuit on a terminal winding reduces inductance of the coupler. The effect on the bus is the same as that of removing the coupler from the bus. The same effect is caused by a broken core.

- An open terminal winding or a severed terminal stub results in maximum inductance introduced into the bus, constituting a load equal to the terminal design load.

Preliminary results indicate that electromagnetic and radiofrequency interference (RFI) characteristics of the current mode bus are favorable.

Table A-2. Bus Medium Failure Modes and Effects

Type of failure \ May affect	Own unit	Related units	Unrelated units	Total system
Bus wire short or open	Improbable	Improbable	Improbable	Improbable
Short circuit in T-coupler	Improbable	Improbable	Extremely improbable	Extremely improbable
Open circuit in T-coupler	Improbable	Improbable	No effect	No effect
Transmitter solid high	Improbable	Extremely improbable	Extremely improbable	Extremely improbable
Transmitter solid low	Improbable	Extremely improbable	Extremely improbable	Extremely improbable

(a) Voltage Mode Bus Medium

Type of failure \ May affect	Own unit	Related units	Unrelated units	Total system
Bus wire short or open	Extremely improbable	Extremely improbable	Extremely improbable	Extremely improbable
Short circuit in T-coupler	Improbable	Improbable	No effect	No effect
Open circuit in T-coupler	Improbable	Improbable	No effect	No effect
Transmitter solid high	Improbable	Extremely improbable	No effect	No effect
Transmitter solid low	Improbable	Extremely improbable	No effect	No effect

(b) Current Mode Bus Medium

Extremely improbable

Improbable

No effect

A.1.6 FIBER-OPTIC BUS

With achievement of low attenuation of the light in an optical fiber and reduced overall cost, fiber optics has become a contender as a transmission medium. Among the major advantages of fiber optics (ref A-6, p. 190) are no pickup of external electromagnetic fields, no RFI, or crosstalk; elimination of grounds and shorts in cabling; large bandwidths for the small size; light weight; and high temperature properties. For avionic applications, single multimode, graded index fibers will probably predominate as light waveguides until gigahertz bandwidths are required or optical switching techniques become a major requirement in data processing and handling.

The most likely approach to be taken will be several small fiber-optic cables combined into a harness. A harness will allow more flexibility and, in addition, will provide better protection for individual fibers. A harness containing several cables is only slightly larger and heavier than a single cable containing several fibers.

With the high bandwidths of fiber optics and the typically low data rate of the network, conventional TDMA multiplexing techniques will suffice for almost any conceivable situation.

The connectors mating the components of a fiber-optic data bus system are the main sources of attenuation. Multiport star couplers that meet military requirements are currently being produced. Their intrinsic loss figures are at the 2-dB level, and future development is not expected to significantly improve their performance. Within a year, a fiber-optic connector suitable for avionics use will be available.

Page

A.2.0 MICROPROCESSORS

A.2.1 INTRODUCTION

Semiconductor microprocessor technology driven by ever-increasing memory demands will be the focal point of this decade and will provide the never-ending increased complexity leading to very-large-scale integration. Today, 64K dynamic RAMs are in production and 256K to 1M bit dynamic RAMs are expected in the next few years. As more memory is placed on a chip, single-chip microcomputers will continue to grow in capability and complexity. By building higher level functions into hardware and firmware, software requirements can be simplified. Special applications (such as signal processing, control applications, etc.) are very likely to be achieved by special-purpose processors with onchip memory. Logic arrays represent another alternative available for special applications. Logic arrays, coupled with computer-aided design (CAD), can provide the system designer with a universal, flexible component. Logic arrays with 10 000 or more uncommitted gates will be available soon. The key to effective use of logic arrays resides in development of sophisticated design-automation technology.

A.2.2 MICROELECTRONICS TECHNOLOGY

A.2.2.1 HISTORICAL DEVELOPMENT

Today's microelectronics had its beginnings with the invention of the transistor at Bell Telephone Laboratories in 1947. Around 1960, with the development of the planar process, miniaturization was extended from discrete devices to the integrated-circuit level. Later in that decade, manufacturing technology was improved with advances in photolithography, ion implantation, and diffusion. The epitaxial process was also developed during this time. In the mid-1960s, metal-oxide-semiconductor (MOS) transistor circuitry was developed. Although it had a speed disadvantage with respect to the bipolar process, it was denser and easier to fabricate.

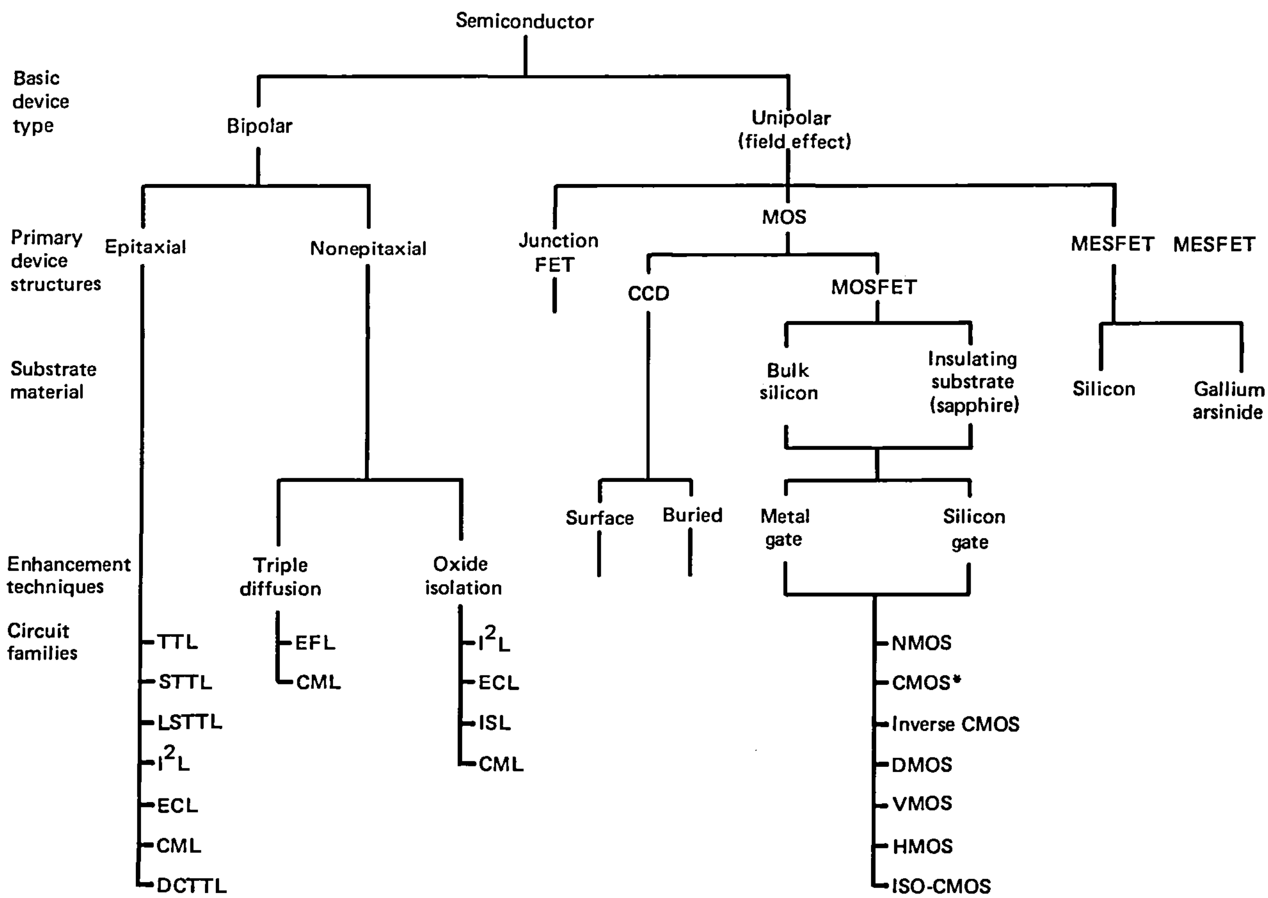
Intensive efforts in the late 1960s enhanced the speed of the MOS devices. At the same time, work on bipolar technology resulted in new structures that were denser and easier to fabricate. The result of these efforts was even faster bipolar, so that while MOS was cheaper, the bipolar still held the speed advantage. While the number of components per

chip has approximately doubled each year, the cost has declined, resulting in increased usage of the devices with increasing performance.

The preceding discussion is extracted from Reference A-7, which is frequently consulted for this survey area.

A.2.2.2 DIGITAL TECHNOLOGY

Semiconductor logic is primarily realized through electronic switches implemented in silicon in two basic ways: the charge-controlled bipolar and the voltage-controlled unipolar transistors. Figure A-4 (from ref A-8) shows how these two basic types have proliferated through technological modifications to the complex variety of today.



*Includes CMOS/SOS, which is creating much interest for military applications.

Source: Honeywell (ref A-8, p. 3)

Figure A-4. Semiconductor Technologies

Differences in the devices are caused partly by attempts at reducing the size and parasitic capacitance associated with the isolation areas between bipolar devices. Device structures for the driver device and load account for further differences. Often a transistor is used as an active load to conserve both area and power. In complementary metal-oxide semiconductor (CMOS), for example, a negative metal-oxide semiconductor (NMOS) driver would be combined with a positive metal-oxide semiconductor (PMOS) load. Because either one or the other is always off, there is very little quiescent current. In integrated injection logic (I^2L), a lateral positive-negative-positive (pnp) transistor acts as a load.

In terms of gate size, I^2L is the smallest, followed by NMOS, PMOS, CMOS, and transistor-transistor logic (TTL). In the past, size reductions have resulted from structural modifications, but through recent innovative masking techniques, scaling of dimensions has taken the lead. A larger fraction of the chip, however, is now used to interconnect the functional elements.

CMOS and NMOS are moving into the classical bipolar linear application areas. NMOS and its high-performance metal-oxide semiconductor (HMOS) version are and will continue to be the dominant technologies. Schottky TTL digital technology is in fact losing its market share to NMOS. The CMOS market, along with the new selective-oxidation CMOS (SOCMOS), will also continue to expand rapidly. Table A-3 (from ref A-8) compares the technologies. The delay-power product is representative of the energy required for a single switching operation.

Table A-3. Comparison of Technologies

Technology	PMOS	NMOS	CMOS	TTL	ECL	I^2L
Area per gate, $mm^2 \times 10^{-3}$ (mil^2)	5 to 8 (8 to 12)	4 to 5 (6 to 8)	7 to 20 (10 to 30)	13 to 39 (20 to 60)	13 to 32 (20 to 50)	3 to 4 (4 to 6)
Propagation delay per gate, ns	100	40 to 100	15 to 50	3 to 10	0.5 to 2	5
Static power per gate, mW	2 to 3	0.2 to 0.5	0.001	1 to 3	5 to 15	0.2
Delay-power product, pJ	200	10 to 50	3	10	10	1
Major process steps	12	14	18	20	24	15
Interfacing ease	Poor	Reasonable	Reasonable	Excellent	Excellent	Good

Source: Honeywell (ref A-8, p. 7).

A.2.2.3 ANALOG TECHNOLOGY

A variety of electronic components is needed to implement an avionic system. In addition to the microcomputer, circuitry must be available to interface with sensors, actuators, and displays. The elements required include line drivers, multiplexers, level shifters, and data converters. In the future, many of these peripheral functions will be included as an integral part of the specialized microcomputer chip. Meanwhile, they are being implemented so that they are compatible with the technology used to produce the microcomputers.

MOS is the most common technology for most microprocessors, peripherals, and memories today. Consequently, when medium-performance analog functions are satisfactory, they are implemented in MOS.

Perhaps the most important analog element is the analog-to-digital converter (ADC). Progress in the development of these devices has been rapid, and many approaches have been used to perform the conversion. Most devices are either successive approximation using a digital-to-analog converter or integrating converter. Conversion times as fast as 1 μs have been attained for the former type, while resolutions to 16 bits have been produced with the latter type.

CMOS processing is moving into bipolar areas for high-resolution, high-speed linear components. The high packing density possible with CMOS allows a smooth link between the digital circuitry and the analog signal processing elements. Consequently, most high-resolution (14 and 16 bit) digital-to-analog converters are being implemented in CMOS.

Even in the high-speed area, CMOS is challenging bipolar; 6- and 8-bit ADCs with 10-MHz cycle rates are appearing mainly in bipolar. Presently, however, 9 bits is the limit for bipolar monolithic devices. The high packing density and low power consumption advantages of CMOS are enticing developments in this process. A 6-bit CMOS ADC with 15-MHz sample rate has already been fabricated, and an 8-bit device is on the way.

In the area of high-speed operational amplifiers, bipolar is still dominant. Improvements have been made in lowering voltage noise without losing gain, speed, or bandwidth. High speed, broad bandwidth, low bias, and offset CMOS chopper operational amplifiers are being offered.

A.2.2.4 CURRENT AND FORECASTED PARAMETERS

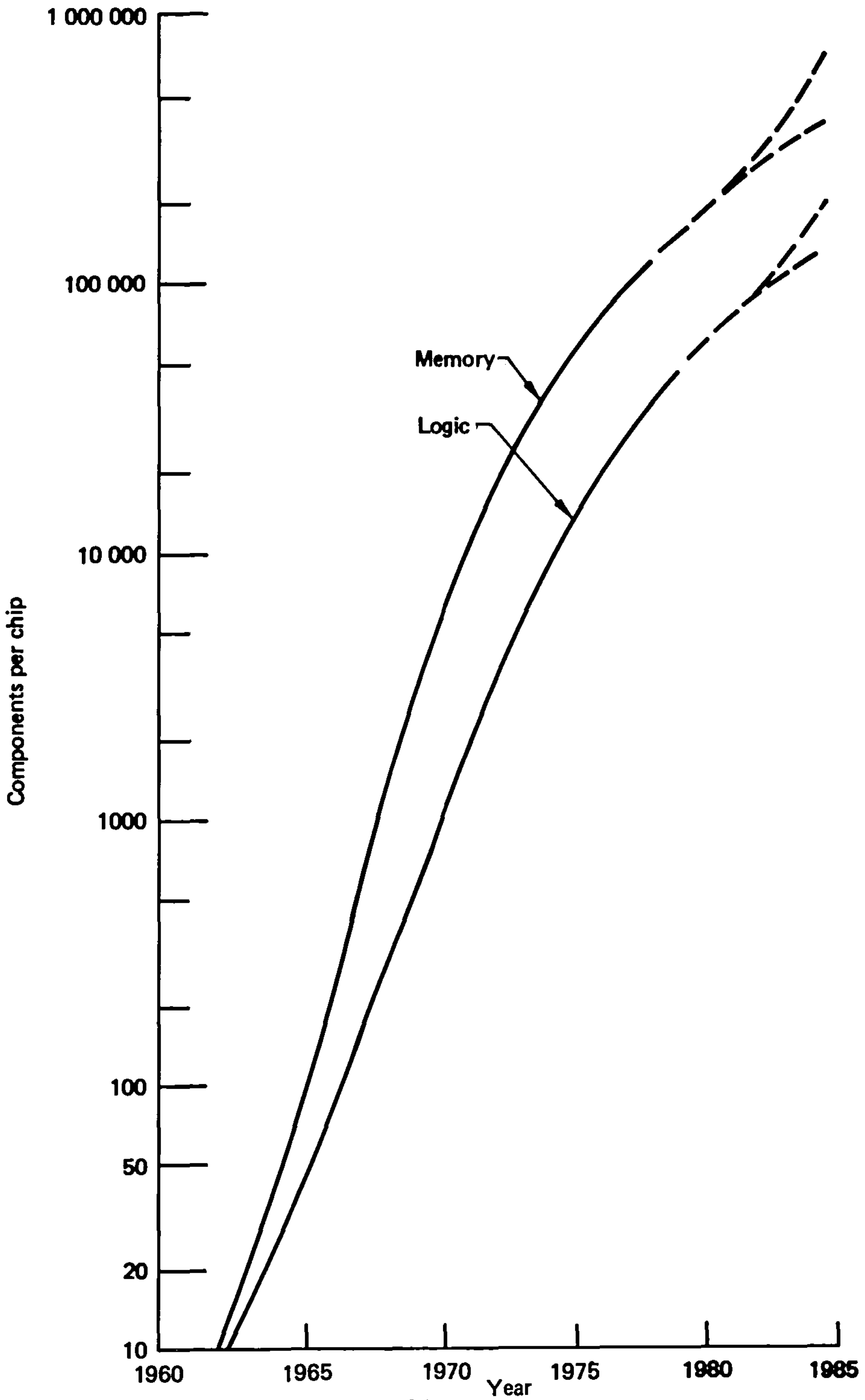
Density and Size—Logic gate size and hence density are related to a number of factors. Among these are the basic dimensions, device structure, and depletion-layer thickness in the substrate. For MOS devices, as the channel length is reduced, there is eventually a length where punchthrough between the source and drain areas occurs. To overcome this, the operating voltage must be reduced and the doping concentration increased. However, there is a limit, as gate field must be increased with doping. The ultimate lower size limit on MOS devices has been estimated at 1.2 μm on a side. For bipolar devices, similar considerations lead to a postulated device size of 1.8 μm per side (ref A-7).

Current NMOS production feature sizes have reached an average of 4 μm, with one vendor producing an HMOS in large quantities at 2 μm. The physical limits mentioned previously should be reached by the end of the decade. In fact, special products have been produced already at 1.5 μm. The key to reduced dimensions in production runs is the technology of E-beam and X-ray lithography. A new development in the X-ray field from Bell Laboratories (ref A-9) looks like a commercially attractive contender.

A substantial increase in circuit density is forecast for the long term, as shown in Figure A-5 (from ref A-10).

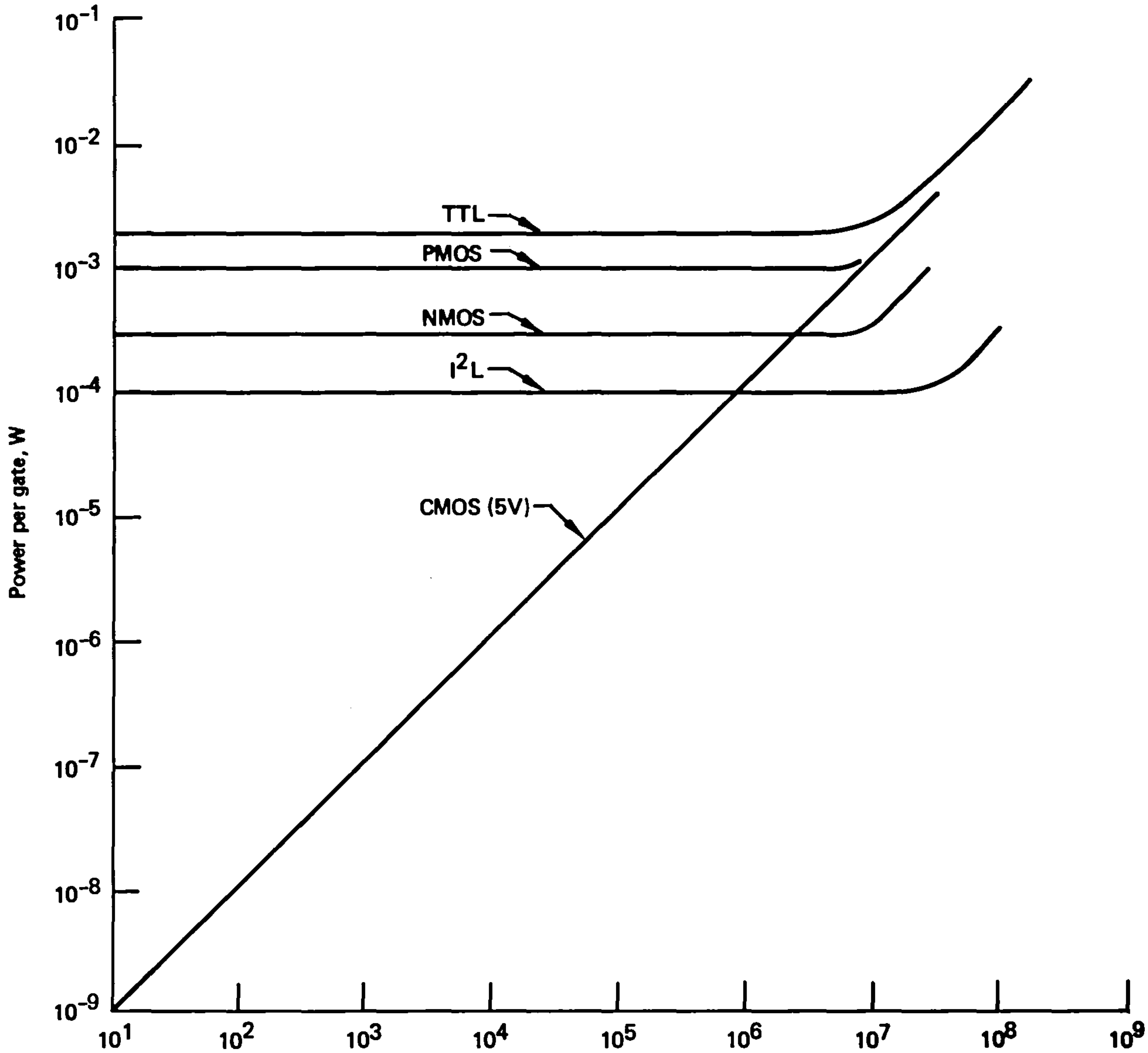
Speed and Power—Speed and power, for both MOS and bipolar devices, can be discussed together as they must be traded-off. Speed is dependent on the ability of the switch to discharge node capacitances and is proportional to the output node capacitance. The node capacitance is itself dependent on the device area, dielectric thickness, substrate doping, and interconnecting line widths. With small node capacitances and channel lengths (L) of several micrometers, the intrinsic delay is proportional to L^2. As L approaches 1 μm, the delay becomes approximately linearly proportional to L.

For a fixed-supply voltage, power dissipated by a gate is proportional to the operating current. Figure A-6 (from ref A-7) shows power dissipation as a function of frequency for the different technologies.



Source: Reference A-10, p. 85.

Figure A-5. Integrated Circuit Density



Source: Reference A-7, p. 25.

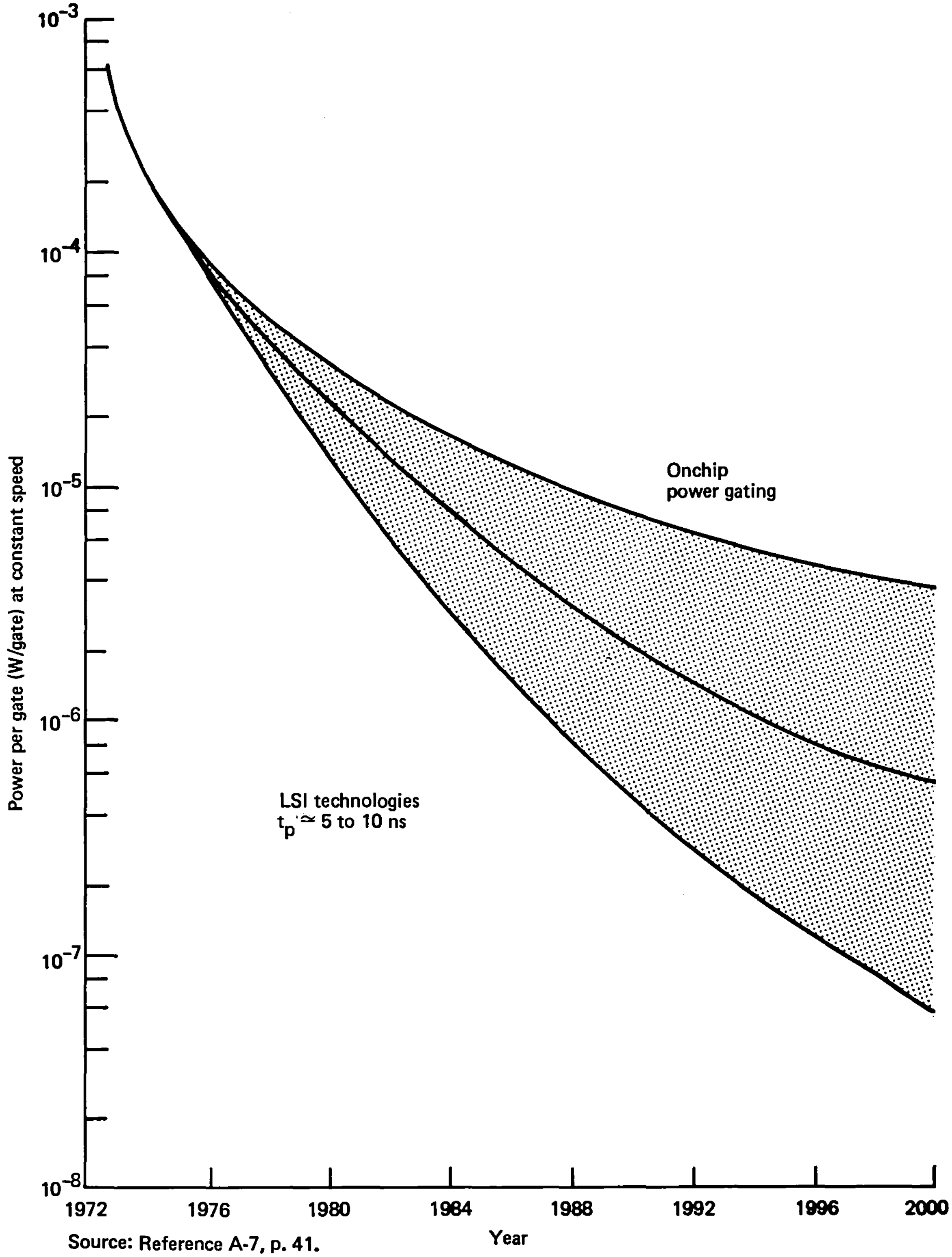
Figure A-6. Power Dissipation for Large-Scale Integration Techniques

Gate speeds for both MOS and bipolar devices are expected to follow reductions in gate area down to about 0.5 ns per gate before leveling off. Figures A-7 and A-8 show projections of expected power dissipated per gate at constant speed and speed (delay) per gate at constant power versus time (from ref A-7).

Reliability—In the past, chip failures in integrated circuits were not as significant as offchip failures. With the increase in functional density per chip today and the decrease in number of external connections, the significance of problems on the chip itself has increased.

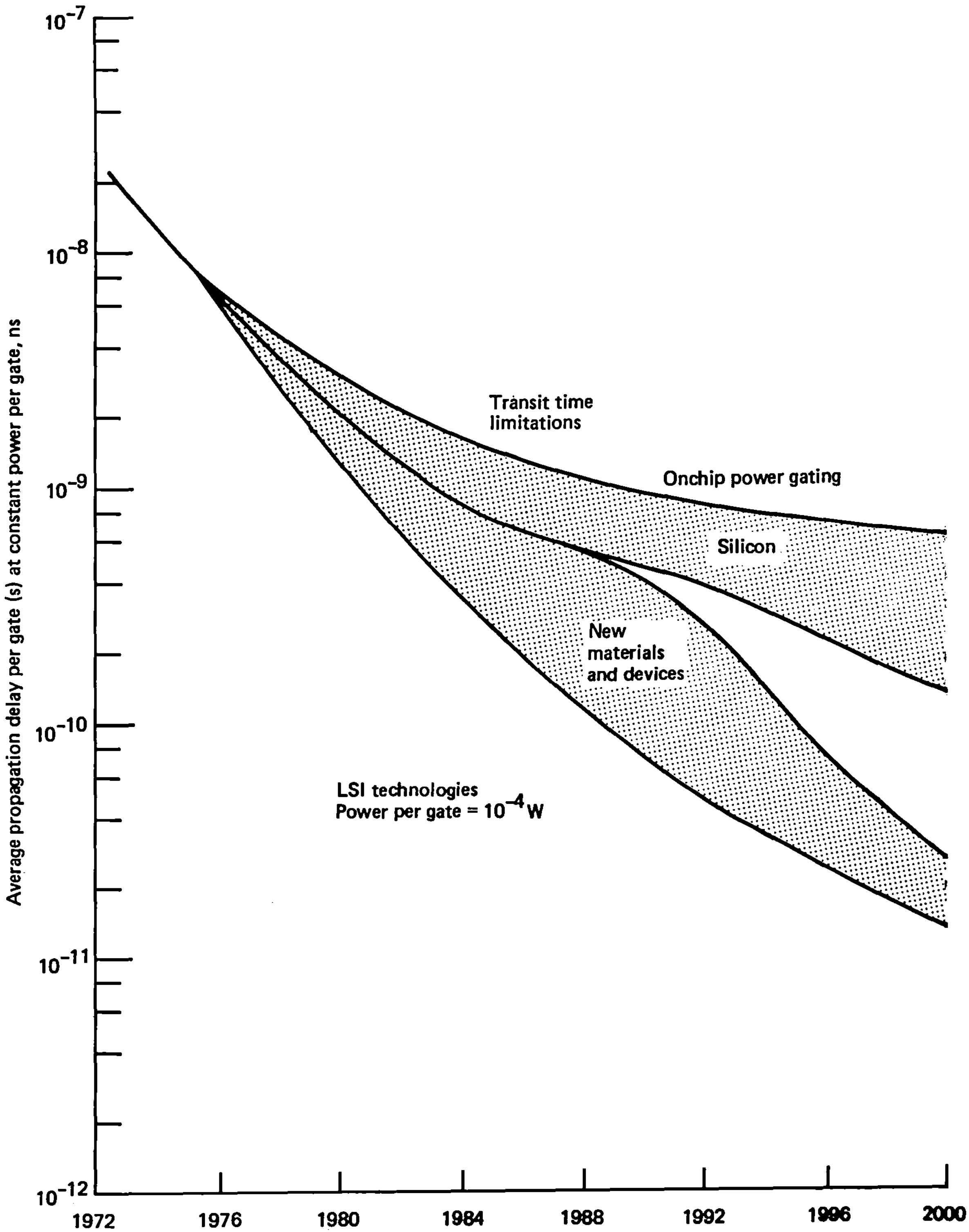
Failures on the chip include those failures caused by metallization problems, diffusion phenomena, and surface or oxide effects. Surface or oxide effects account for a sizable fraction of failures in MOS devices. Reports by manufacturers indicate failure rates for both MOS and bipolar devices are well under 0.1% per 1000 hr at 70°C (158°F) at a confidence level of 90% (from ref A-7).

Cost—The cost of an integrated circuit includes packaging and testing in addition to the cost of the processed die. The cost per packaged gate has been derived by forecasting gate packing density and cost per unit area. The cost per packaged gate is shown in Figure A-9 (from ref A-7). Although the cost per chip may even increase slightly in the future, because of the increase in gate density, shown in Figure A-10 (from ref A-7), the result is a decrease in functional cost.



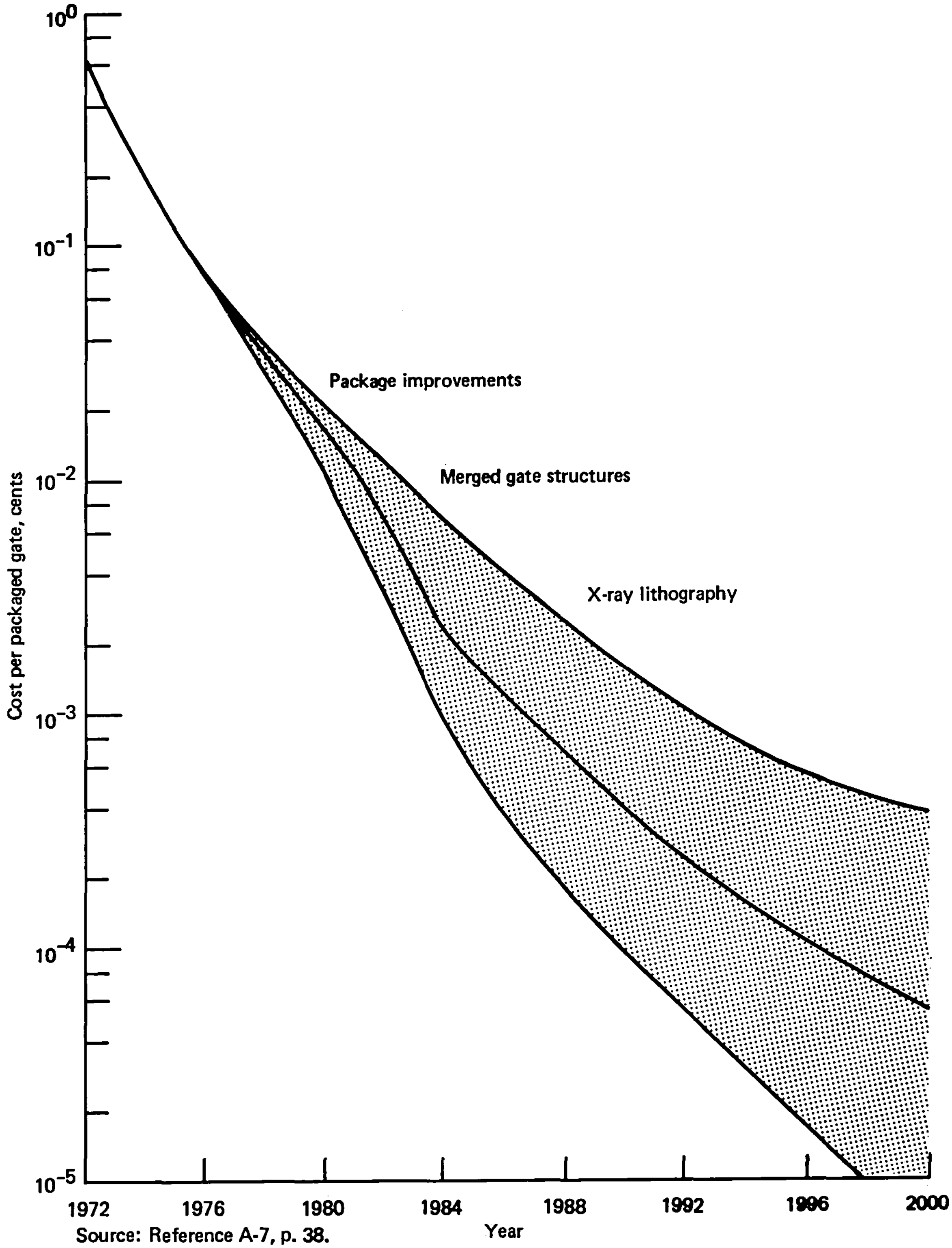
Source: Reference A-7, p. 41.

Figure A-7. Forecast of Power per Gate at Constant Speed



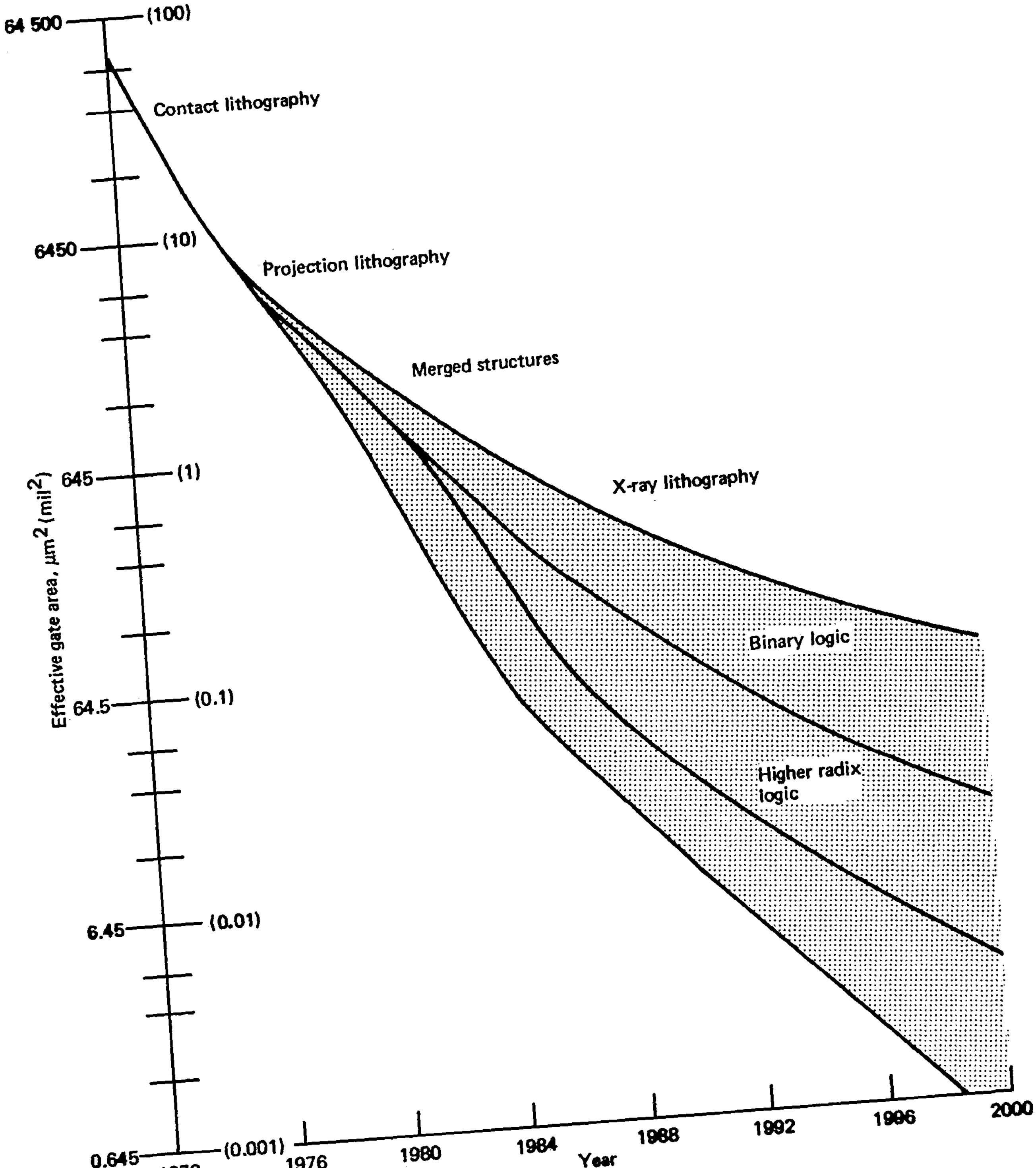
Source: Reference A-7, p. 42.

Figure A-8. Forecast of Speed per Gate at Constant Power



Source: Reference A-7, p. 38.

Figure A-9. Forecast of Cost per Packaged Gate



Source: Reference A-7, p. 37.

Figure A-10. Forecast of Gate Density

A.2.2.5 TECHNOLOGY FORECAST

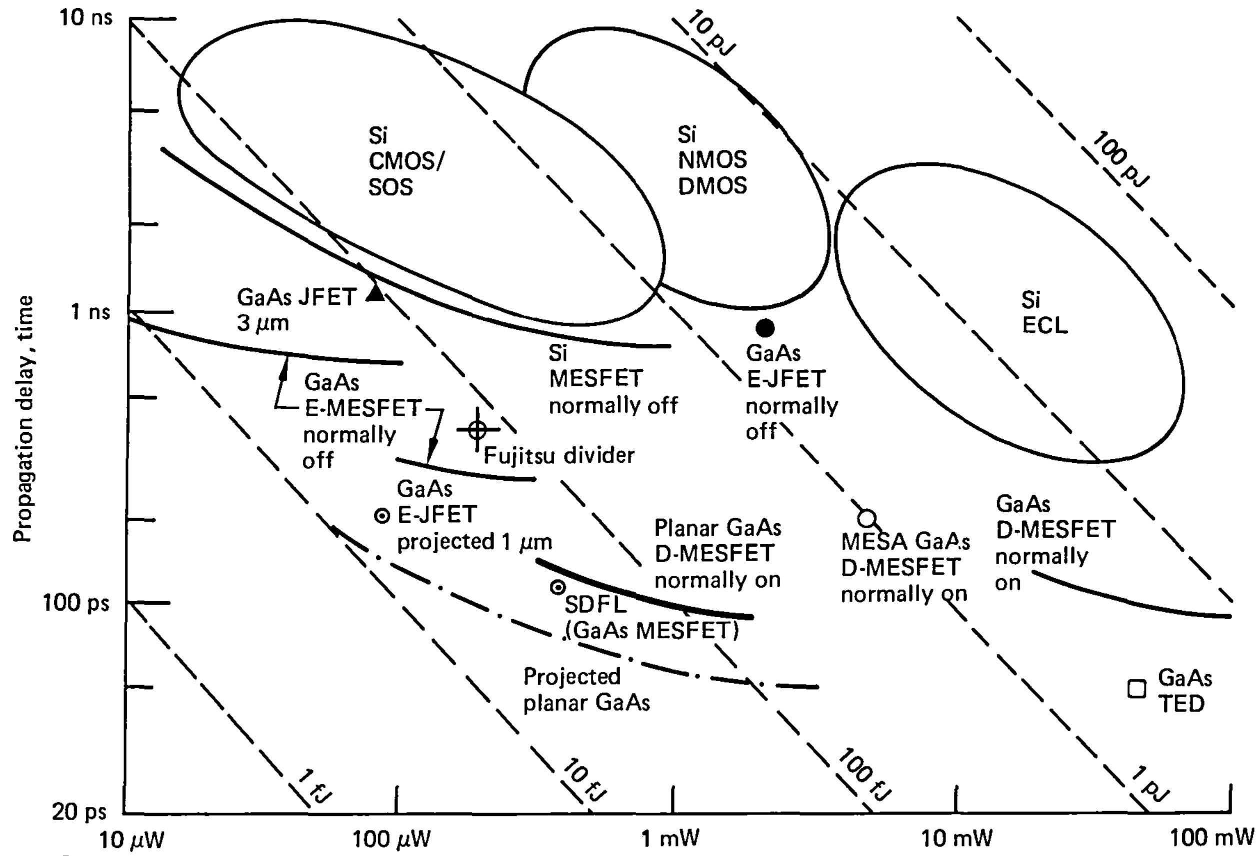
Much of the recent progress in microelectronic technology has resulted from advances in ion implantation methods for doping, isolation of cell walls, and photolithography. A significant amount of development effort is going into projection printing and direct printing with E-beam or X-ray techniques. These methods will avoid mask damage problems, which can lead to onchip defects. Engineers at Bell Laboratories have developed an X-ray system that is smaller, less expensive, and more reliable than previous ones. The system uses a smaller exposure power, which is feasible because of a more sensitive resist. In addition, control of line width with the system is better than 0.1 μm across the wafer. Most important for commercial applications, it has been forecast to be cost competitive (ref A-9).

Developments such as those mentioned previously have allowed production of novel device structures aimed at improving performance. Most of the technologies still use silicon in one form or another; however, use of materials such as gallium arsenide (GaAs) is being explored as well.

One of the promising bipolar technologies is I^2L. Packing densities similar to those of MOS have been obtained. Because of process similarity, I^2L devices can be included on the same chip with Schottky TTL, emitter-coupled logic (ECL), and other circuit forms. This advantage can help reduce interface circuit requirements.

Silicon on insulated substrate MOS (SOISMOS) is another promising silicon technology. In this device, a thin film of silicon is grown on an insulating substrate such as sapphire. Islands of silicon are then formed by selective etching. The technique results in both size reduction and lower capacitance characteristics and, consequently, higher speed and lower power requirements. A SOISMOS chip would be roughly 20% to 30% smaller than the equivalent NMOS device (ref A-5). Also, GaAs may provide ultra-high-speed circuitry.

Because GaAs has an electron mobility five times that of silicon, electron devices implemented using it can have smaller power-delay products. In addition, the electron devices will sustain higher temperatures and greater nuclear hardening. Figure A-11 (from ref A-8) relates three GaAs technologies–enhanced junction field-effect transistor



Source: Honeywell (ref A-8, p. 23).

Figure A-11. Speed and Power Performance of Various Technologies

(E-JFET), metal semiconductor field-effect transistor (MESFET), and transfer electron devices (TED)—to the competing silicon technologies.

Although the potential advantages of using GaAs are real, large volume production of high-complexity circuits has had both material and processing problems. The defect density has been two orders of magnitude higher than that for silicon (ref A-10).

A fundamentally different type of device has been developed by Lincoln Laboratory (ref A-11). The permeable-base transistor (PBT) has an array of tungsten fingers 0.16 μm wide formed on a substrate. A crystal is then grown through and around the fingers. Electrons flow from the emitter substrate through the comblike structure to the collector. The current is controlled by the voltage potential applied to the fingers. Peak operating frequencies are forecast to reach 500 GHz—several times that of other devices. The concept has been implemented in GaAs, but can also be fabricated in silicon.

Table A-4 and Figure A-12, from an article by R. Connolly (ref A-12), indicate the Department of Defense (DOD) goals for its Very-High-Speed Integrated Circuit (VHSIC) Program. To illustrate the extremely rapid progress, due largely to fierce competition, Hewlett Packard has produced a demonstration single-chip microcomputer with 450 000 gates (ref A-13). This meets some of the mid-1980s VHSIC goals.

Table A-4. Device and Chip Capability, Large-Scale Integration and Very-Large-Scale Integration

Parameter	1979 capability		Mid-1980s capability	
	Silicon MOS	Silicon bipolar	Silicon MOS	Silicon bipolar
Feature size, μm	2.5	2.5	0.5	0.5
Gates per chip	5000	5000	250 000	250 000
T_{PD} = propagation delay, ns	25	5	5	1
Gate power-delay product, pJ	2	2	0.02	0.08
Maximum frequency, f_{max} (1/4 T_{PD}), MHz	50	50	50	250
Chip area, mm^2 (mil^2)	6.35 x 6.35 (250 x 250)	6.35 x 6.35 (250 x 250)	10.2 x 10.2 (400 x 400)	10.2 x 10.2 (400 x 400)
Typical device type	NMOS	npn	NMOS	npn
Throughput, f_{max} x gates/chip	5×10^4	2.5×10^5	1.25×10^7	6.25×10^7

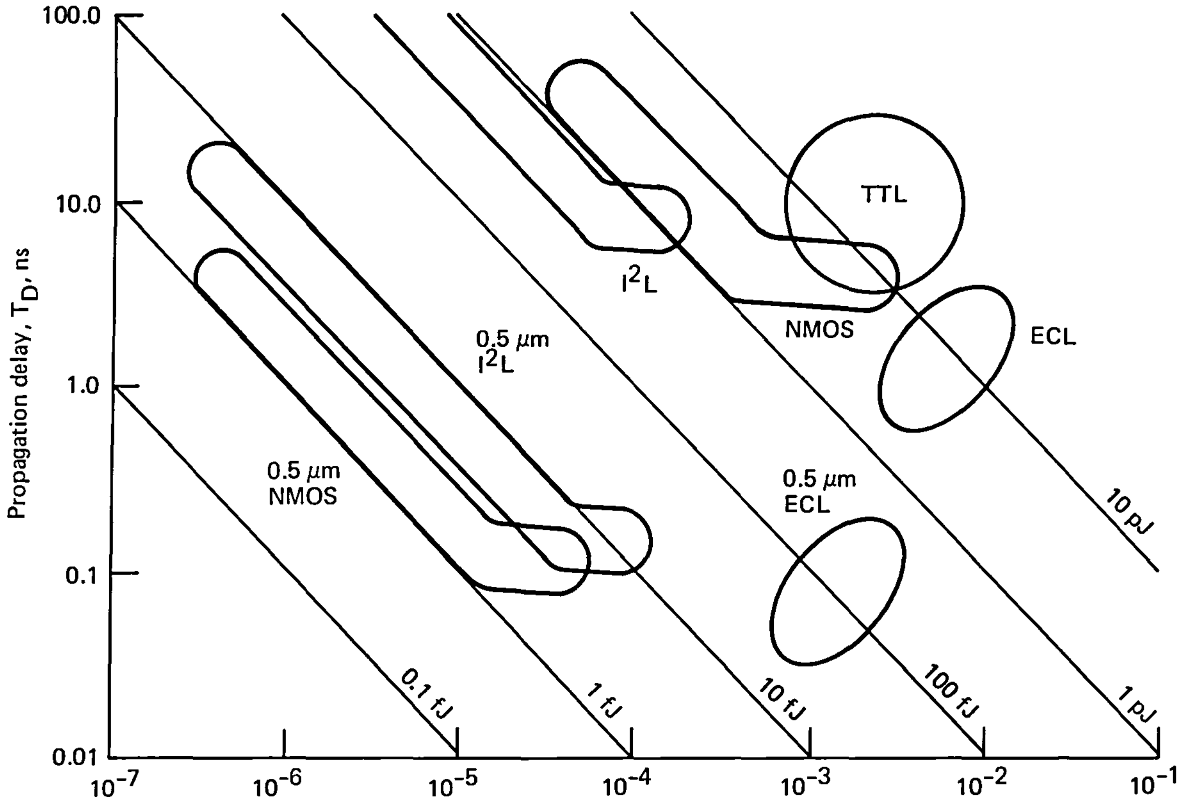
Source: Reference A-12, pp. 81-85.

A.2.3 MICROCOMPUTERS

By way of explanation, a computer is an assembly that contains the following functional elements:

- Arithmetic logic unit (ALU)
- Processor control and executive
- Input conditioning
- Output conditioning
- Memory

A processor, however, generally includes only the first two elements. The remaining elements must be added to produce a computer.



Source: Reference A-12, pp. 81-85.

Figure A-12. Very-High-Speed Integrated Circuit Goals

The first monolithic large-scale integrated circuit (LSIC) digital processor—the Intel 4004, a 4-bit machine—was introduced in 1972. Fabricated of PMOS technology, it had 46 instructions and an instruction cycle time of 10.8 μm (ref A-7). Since that time, the numbers and types of microprocessors have increased to where about 50 companies now offer such products (ref A-14).

It has become more difficult to distinguish between microcomputers and minicomputers. In general, a microcomputer consists of one or a few chips; while a minicomputer, being more flexible and general purpose, is built around microcomputer chips. Recently, however, microcomputers have assumed the performance of medium-sized mainframes. For the application of interest—airborne avionics—microcomputers will easily supply performance requirements (ref A-5).

A.2.3.1 CURRENT MICROPROCESSORS AND MICROCOMPUTERS

Available microprocessors and microcomputers range from simple 1-bit logic machines to 32-bit micromainframe computers. They are available with extensive hardware and software development support and their numbers are growing dramatically. A comparison of 8- and 16-bit processor types available in 1979 (ref A-15) versus those available in 1981 (ref A-16) shows an increase in both types by a factor of three. This growth factor, if maintained for the next 8 years, would mean that several hundred types of these categories of general-purpose microprocessors would be available.

A.2.3.2 COMPUTER TECHNOLOGY FORECAST

A number of reviews and projections of computer technology for avionics have been done. Reference A-7 is a survey commissioned by the Federal Aviation Administration (FAA) during 1976 and 1977 and was published as a book in 1980. Reference A-7 estimates cost, speed, and power—among other parameters—for avionic computers for the next 20 years. Those projections will be used extensively.

The early-generation microprocessors ranged in size from 19 to 26 mm^2 (30K to 40K mil^2) in chip area. Those chips, which became available in 1977, contained significant amounts of memory and had grown to a range of 32 to 39 mm^2 (50K to 60K mil^2). Figure A-13 (from ref A-7) from the FAA survey forecasts how such advances and technology can lead to reduced costs for these microcomputers.

With the continued decrease in microcomputer chip cost, the packaged cost of the total system will be found increasingly in the chassis, input/output (I/O) connectors, and other components. Reduction in size and power requirements should, however, contribute to a reduction in total system cost.

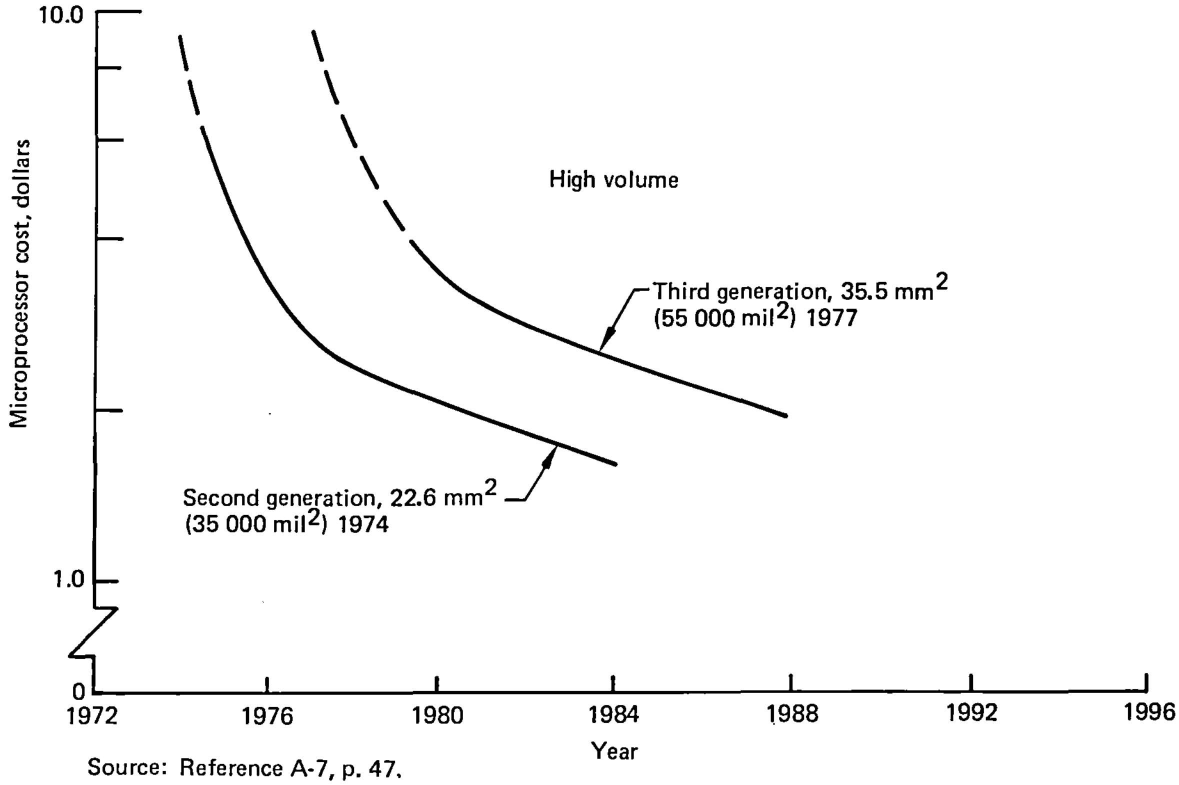
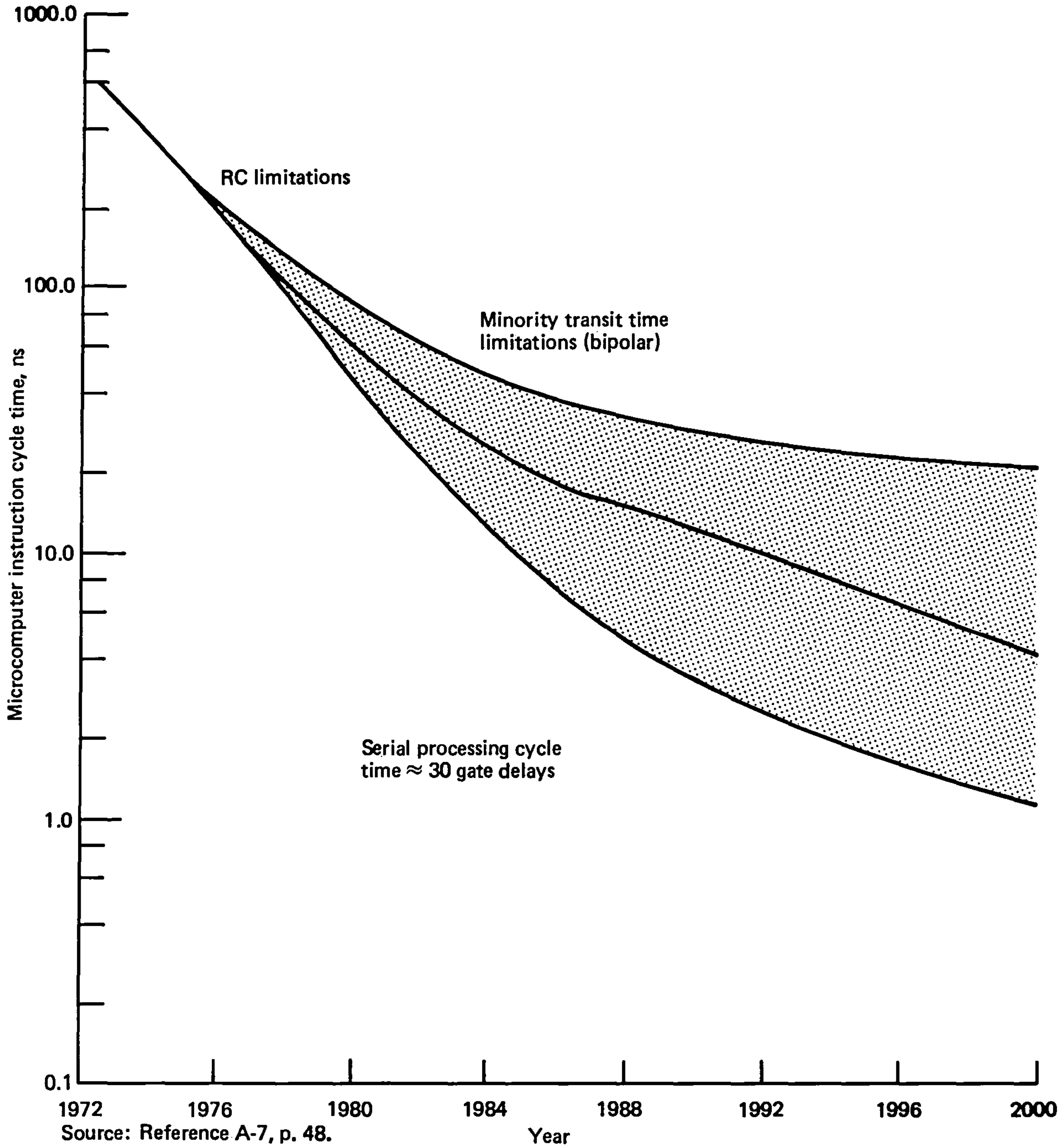


Figure A-13. Forecast of Cost of Third-Generation Microcomputer

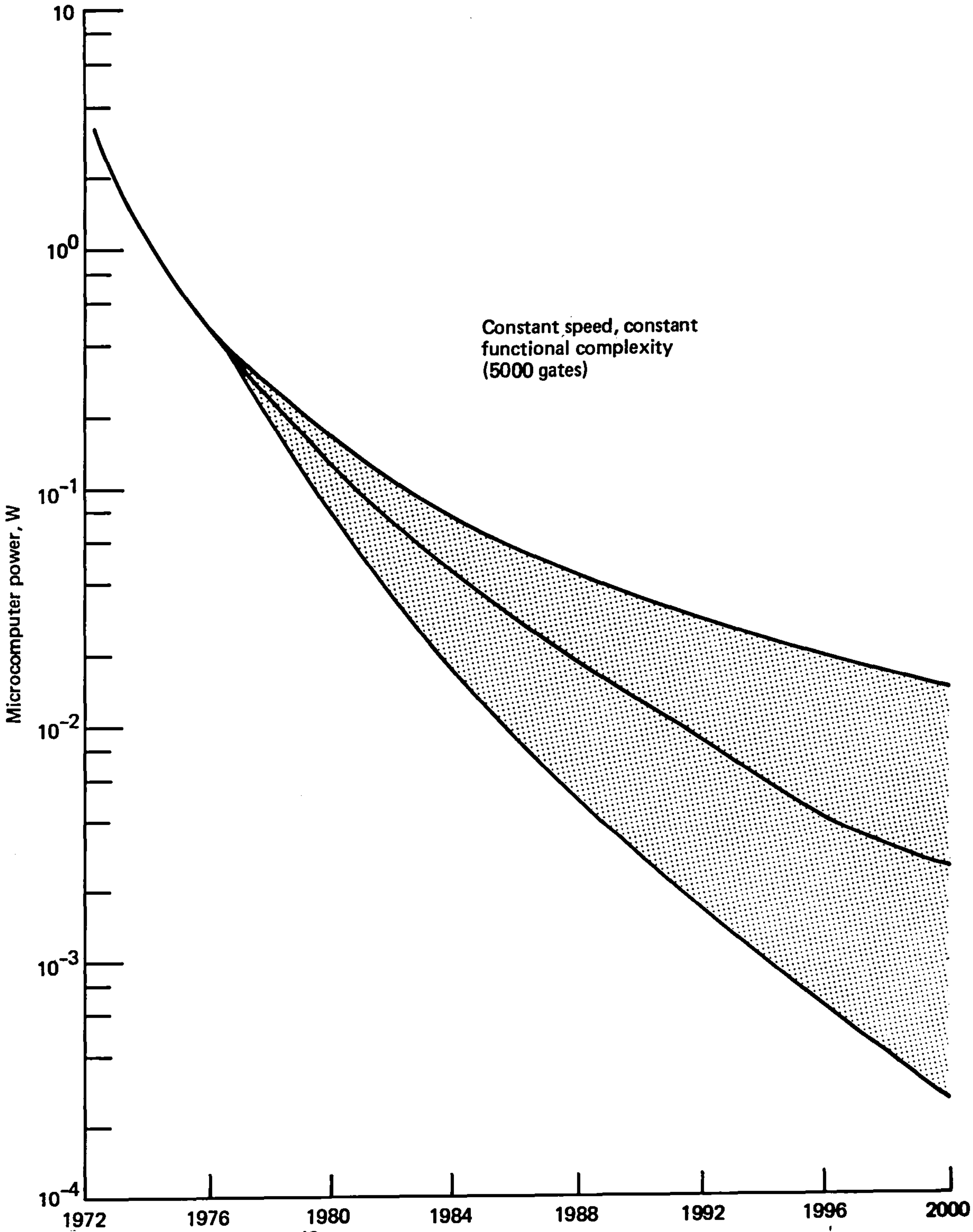
Figure A-14 (from ref A-7) displays anticipated instruction cycle time (register-to-register add time) for future microprocessors. These times are typically composed of from 20 to 40 gate delay times for serial processors. Of course, introduction of new architectures can lead to even shorter effective cycle times.

The power dissipated by a microcomputer closely follows the power per gate requirements. Each new generation of microcomputer using more advanced process technology can be expected to provide higher speeds as well as power requirements per function. Holding speed and functional complexity constant, as shown in Figure A-15 (from ref A-7), forecast dramatic drops in power requirements in the future.



Source: Reference A-7, p. 48.

Figure A-14. Forecast of Instruction Cycle Time



Source: Reference A-7, p. 49.

Figure A-15. Forecast of Microcomputer Power Requirements

A.2.4 MEMORY DEVICES

Semiconductor memories consist of two basic types. Read-only memory (ROM) generally has a long read and write cycle and hence cannot be used for temporary storage. Its most important characteristic is its ability to retain memory when power is lost. Random-access memory (RAM) is used where loss of power can be tolerated or where a battery backup is available. It is used if reading and writing of information are required.

Many technologies have been used to implement semiconductor memory. The choice depends on the required speed of access, density, and power dissipation. Tables A-5 to A-8 (from ref A-8 by way of ref A-17) compare military-qualified devices available in 1979 and present four applications: fast write, main memory, fixed program memory, and mass memory.

One alternative to solid-state memory is magnetic bubble memory, which can provide high densities with nonvolatility to power loss. Because this device is made using techniques similar to those used for integrated circuits, cost per bit can be brought down through mass production. Access times are slower than those of semiconductor memory because they operate serially. However, magnetic bubble memory occupies less volume than either semiconductor memories or floppy disks.

Table A-5. State of the Art in Memory Components for Fast-Write Applications

	ECL	TTL		I^2L		MNOS (static)	CMOS		CMOS/SOS		MNOS[a]	MNOS/SOS[b]	Plated wire	Core
	Com	Com	Hardware	Com	Hardware	Com	Com	Hardware	Com	Hardware	Hardware	Hardware	Hardware	Com
Volatility	V	V	V	V	V	V	V	V	V	V	NV	NV	NV	NV
Readout	NDRO	NDRO	NDRO	NDRO	NDRO	NDRO	NDRO	NDRO	NDRO	NDRO	NDRO	NDRO	NDRO	DRO
Read access time, ns	15	75	60	10	50	500	200	700	85	200	700	350	350	350
Write cycle time, ns	15	75	60	10	100	500	200	700	85	200	1000	1000	800	700
Average module power consumption, μW/bit	650	400	500	800	100	20	5	10	0.1	3	1000	200	200	4000
Operating temperature range, °C (°F)	0 to +70 (+32 to +158)	0 to +70 (+32 to +158)	-55 to +125 (-67 to +257)	0 to +75 (+32 to +167)	-55 to +125 (-67 to +257)	0 to +125 (+32 to +257)	0 to +125 (+32 to +257)	-55 to +125 (-67 to +257)	0 to +125 (+32 to +257)	-55 to +125 (-67 to +257)	-55 to +125 (-67 to +257)	-55 to +125 (-67 to +257)	-55 to +80 (-67 to +176)	-55 to +95 (-67 to +203)
Retention of data, hr	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	>48	>10	∞	∞
Endurance (maximum cycles)	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	$>10^{12}$	$>10^{12}$	∞	∞
Chip capacity, bits	1K	4K	256	16K	4K	16K	4K	512	4K	1K	256	512	N/A	N/A
Typical module capacity, bits	32 000	32 000	8000	32 000	32 000	32 000	32 000	32 000	32 000	32 000	3000	32 000	32 000	2000
Relative reliability, (0 to 10 scale), module	1	1	1	1	2	1	1	3	3	5	1	1	2	5
System cost per bit, cents	2	1.5	80	3	10	1	3	30	7	30	10	40	180	5
Noise immunity	Average	Good	Good	Poor	Poor	Average	Excellent	Excellent	Excellent	Excellent	Good	Good	Good	Good
Voltage requirements	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Poor	Poor	Good	Good
Interface complexity	Average	Good	Good	Fair	Fair	Fair	Average	Average	Average	Average	Poor	Poor	Fair	Fair
Maturity (0 to 10 scale)	8	7	9	5	5	7	10	9	3	3	5	3	10	10
Ease of design	Average	Good	Good	Fair	Fair	Good	Excellent	Excellent	Excellent	Excellent	Fair	Fair	Poor	Good
Second sourceability	Fair	Fair	Excellent	Good	Good	Excellent	Good	Good	Fair	Fair	Fair	Poor	Poor	Excellent
Manufacturability	Fair	Good	Excellent	Excellent	Excellent	Excellent	Good	Fair	Fair	Poor	Poor	Poor	Poor	Excellent

[a]PMOS peripherals.
[b]CMOS/SOS peripherals.

Source: Honeywell (ref A-8, p. 65).

Table A-6. State of the Art in Memory Components for Main-Memory Applications

	TTL		I^2L		NMOS (dynamic)	CMOS		CMOS/SOS		MNOS		MNOS /SOS	Plated wire	Core
	Com	Hardware	Com	Hardware	Com	Com	Hardware	Com	Hardware	Com	Hardware	Hardware	Hardware	Com
Volatility	V	V	V	V	V	V	V	V	V	NV	NV	NV	NV	NV
Readout	NDRO	NDRO	NDRO	NDRO	DRO	NDRO	NDRO	NDRO	NDRO	NDRO	NDRO	NDRO	NDRO	DRO
Read access time, ns	100	100	20	100	110	200	700	85	200	1600	1000	500	450	1000
Write cycle time, ns	100	100	20	200	110	200	700	85	200	10^5	10^5	10^5	800	1000
Average module power consumption, μW/bit	250	250	40	50	4	5	10	0.1	3	2	3	1	150	200
Operating temperature range, °C (°F)	0 to +125 (+32 to +257)	-55 to +125 (-67 to +257)	0 to +75 (+32 to +167)	-55 to +125 (-67 to +257)	0 to +70 (+32 to +158)	0 to +125 (+32 to +257)	-55 to +125 (-67 to +257)	0 to +125 (+32 to +257)	-55 to +125 (-67 to +257)	0 to +70 (+32 to +158)	-55 to +125 (-67 to +257)	-55 to +125 (-67 to +257)	-55 to +85 (-67 to +185)	-55 to +95 (-67 to +203)
Retention of data, yr	∞	∞	∞	∞	∞	∞	∞	∞	∞	30	30	30	∞	∞
Endurance (maximum cycles)	∞	∞	∞	∞	∞	∞	∞	∞	∞	10^6	10^6	10^6	∞	∞
Chip capacity, bits	4K	256	16K	8K	64K	4K	512	4K	1K	8K	512	1K	N/A	N/A
Typical module capacity, bits	256K	64K	256K	64K	256K	256K	64K	256K	64K	256K	64K	64K	64K	128K
Relative reliability (0 to 10 scale), module	1	1	1	2	1	1	2	3	2	10	10	10	1	5
System cost per bit, cents	1	80	2	7	0.2	3	25	7	25	2	30	30	100	0.5
Noise immunity	Good	Good	Poor	Poor	Fair	Excellent	Excellent	Excellent	Excellent	Good	Good	Good	Good	Good
Voltage requirements	Good	Good	Good	Good	Good	Good	Good	Good	Good	Poor	Poor	Poor	Good	Good
Interface complexity	Excellent	Excellent	Fair	Fair	Poor	Average	Average	Average	Average	Poor	Poor	Poor	Fair	Fair
Maturity (0 to 10 scale)	10	9	7	5	9	10	9	3	3	5	6	4	10	10
Ease of design	Good	Good	Fair	Fair	Good	Excellent	Excellent	Excellent	Excellent	Fair	Fair	Fair	Poor	Good
Second sourceability	Excellent	Excellent	Good	Good	Excellent	Good	Good	Fair	Fair	Fair	Fair	Poor	Poor	Excellent
Manufacturability	Good	Good	Excellent	Excellent	Excellent	Good	Fair	Fair	Poor	Poor	Poor	Poor	Poor	Excellent

Source: Honeywell (ref A-8, p. 66).

Table A-7. State of the Art in Memory Components for Fixed-Program Applications

	ECL (PROM)	TTL (ROM)		NMOS erasable	NMOS (ROM)	CMOS/SOS (PROM)		MNOS (EAROM)		MNOS /SOS (EAROM)	Amor-phous (RMM)	Plated wire	Core
	Com	Com	Hardware	Com	Com	Com	Hardware	Com	Hardware	Hardware	Com	Hardware	Com
Volatility	NV	NV	NV	NV	NV	NV	NV	NV	NV	NV	NV	NV	NV
Read access time, ns	15	110	60	300	80	100	100	1650	1500	500	200	450	1000
Average module power consump-tion, μW/bit	650	100	200	6	2	6	6	1	0.3	0.1	0.5	150	200
Operating temper-ature range, °C (°F)	0 to +70 (+32 to +158)	0 to +125 (+32 to +257)	-55 to +125 (-67 to +257)	0 to +70 (+32 to +158)	0 to +70 (+32 to +158)	-55 to +125 (-67 to +257)	-55 to +125 (-67 to +257)	0 to +70 (+32 to +158)	-55 to +125 (-67 to +257)	-55 to +125 (-67 to +257)	0 to +70 (+32 to +158)	-55 to +85 (-67 to +185)	-55 to +95 (-67 to +203)
Chip capacity, bits	1K	16K	1K	32K	64K	1K	1K	8K	1K	1K	1K	N/A	N/A
Typical module capacity, bits	32K	64K	16K	64K	64K	64K	64K	64K	64K	64K	64K	64K	64K
Relative reliability, (0 to 10 scale), module	1	3	9	9	9	3	6	10	10	10	2	2	10
System cost per bit, cents	2	1.5	60	0.4	0.2	10	15	2	30	30	20	100	0.5
Noise immunity	Average	Good	Good	Fair	Fair	Excellent	Excellent	Good	Good	Good	Good	Good	Good
Voltage requirements	Good	Good	Good	Excellent	Excellent	Good	Good	Poor	Poor	Poor	Poor	Good	Good
Interface complexity	Average	Good	Good	Good	Good	Average	Average	Poor	Poor	Poor	Poor	Fair	Fair
Maturity (0 to 10 scale)	8	7	3	5	7	4	3	5	2	1	0	10	10
Ease of design	Average	Good	Good	Good	Good	Excellent	Excellent	Fair	Fair	Fair	Poor	Poor	Good
Second sourceability	Fair	Fair	Poor	Good	Good	Poor	Poor	Fair	Poor	Poor	Poor	Poor	Excellent
Manufac-turability	Fair	Good	Poor	Good	Good	Fair	Poor	Poor	Poor	Poor	Poor	Poor	Excellent

Source: Honeywell (ref A-8, p. 67).

Table A-8. State of the Art in Memory Components for Mass-Memory Applications

	CCD	I^2L	CMOS /SOS	MNOS		MNOS /SOS	Magnetic bubble	Core	Disk	Drum	Tape
	Com	Hardware	Hardware	Com	Hardware	Hardware	Com	Com	Com	Com	Com
Volatility	V	V	V	NV	NV	NV	V/NV	NV	NV	NV	NV
Readout	DRO	NDRO	NDRO	NDRO	NDRO	NDRO	NDRO	DRO	NDRO	NDRO	NDRO
Read access time	100 μs	120 ns	200 ns	1.6 μs	5 μs	1 μs	4 ms	1 ms	10 ms	10 ms	Minutes
Throughput rate, K bps	5000	10 000	7000	2000	2000	5000	50	1000	10 000	10 000	10 000
Average module power consumption, μW/bit	30	0.5	3	0.1	1	0.3	10	250	7	8	0.05
Operating temperature range, °C (°F)	0 to +85 (+32 to +185)	-55 to +125 (-67 to +257)	-55 to +125 (-67 to +257)	0 to +70 (+32 to +158)	-55 to +125 (-67 to +257)	-55 to +125 (-67 to +257)	+15 to +35 (+59 to +95)	-55 to +95 (-67 to +203)	0 to +55 (+32 to +131)	-20 to +55 (-4 to +131)	-30 to +65 (-22 to +149)
Retention of data, yr	∞	∞	∞	30	30	30	∞	∞	∞	∞	∞
Endurance, maximum cycles	∞	∞	∞	10^6	10^6	10^6	∞	∞	∞	∞	∞
Chip capacity, bits	64K	4K	4K	8K	4K	4K	92K	N/A	N/A	N/A	N/A
Typical module capacity, bits	10^5	10^6	10^6	10^6	10^6	10^6	10^6	10^5	10^8	10^8	10^{10}
Relative reliability, (0 to 10 scale), module	2	3	2	10	10	10	2	5	1	1	1
System cost per bit, cents	1.5	2	7	1.5	2	20	1.2	0.5	0.08	0.05	0.0001
Noise immunity	Fair	Poor	Excellent	Good	Good	Good	Poor	Good	Good	Good	Good
Voltage requirements	Good	Good	Good	Poor	Poor	Poor	Average	Good	Good	Good	Good
Interface complexity	Fair	Fair	Average	Poor	Poor	Poor	Poor	Fair	Fair	Fair	Fair
Maturity (0 to 10 scale)	5	4	3	5	5	3	1	10	10	10	10
Ease of design	Average	Fair	Excellent	Fair	Fair	Fair	Poor	Good	Fair	Fair	Fair
Second sourceability	Good	Good	Fair	Fair	Fair	Poor	Fair	Excellent	Excellent	Good	Excellent
Manufacturability	Excellent	Excellent	Poor	Poor	Poor	Poor	Poor	Excellent	Excellent	Excellent	Excellent

Source: Honeywell (ref A-8, p. 68).

Page

A.3.0 ACTUATORS AND ACTUATOR CONTROLLERS

Actuators provide power for flight controls, engine controls, thrust reversing, landing gear retraction and extension, nose wheel steering, brakes, wheel well doors, and other functions on commercial transports. Most of these functions use hydraulic actuators. However, recent high-efficiency electric motor and control developments may make electromagnetic actuators competitive with hydraulic actuators in this decade. This section addresses both hydraulic and electromagnetic actuator designs that are expected to be included in design tradeoffs of 1990s commercial transport airplanes. The data are limited to those actuators and controllers likely to power flight control surfaces.

A trade study (ref A-18) conducted by Boeing Military Airplane Company for the Air Force Flight Dynamics Laboratory and Aero-Propulsion Laboratory investigated actuation concepts expected to be available in the 1990s. This section uses the data developed in the interim report because of the thoroughness and timeliness of that effort. Other actuator and controller data derived from sources within Boeing Commercial Airplane Company and from the literature will be referenced as appropriate.

A.3.1 ACTUATOR SYSTEM COMPONENT STUDY CONSTRAINT OVERVIEW

Only hydraulic, electromechanical, and integrated actuator package (IAP) power drive units are treated in this survey. The hydraulic power drive units covered include piston actuators, vane actuators, and multiple-piston motors. The electromechanical drive units covered include ac motors, dc motors, torque motors, stepper motors, and other special units. The IAP types include servopump concepts, accumulator concepts, and fixed-displacement pump concepts.

Actuator output mechanisms commonly used in aircraft include bellcranks, rack-and-pinion gearing, helical or ball splines, spur gearing, threaded powerscrew or ballscrew, and planetary or skip-tooth gearing for hingeline units. The type of output mechanism used will depend on bandwidth requirements, spatial and volumetric limitations, and failure mode requirements (such as a return to "neutral" position). Output mechanisms are not included in this technology assessment, even though there have been many recent innovative designs, because their selection will usually be dependent on the specific application.

Among the hydraulic actuator control valve concepts discussed, those that are adaptable to electrical command include electrohydraulic servovalves, digitally controlled stepper-motor-driven distributor valves, and solenoid valves.

Electromechanical controller concepts usually involve analog or digital drive logic for inverter switching, current limiting, and control law implementation. Clutched EMA systems can cause output shafts to run clockwise, counterclockwise, or to remain fixed; such systems allow the motor to run continuously in one direction, thus eliminating switching requirements and providing other advantages to be described later.

A.3.2 HYDRAULIC ACTUATOR COMPONENTS

Table A-9 summarizes the hydraulic actuation concepts included in this assessment. Various combinations of drive units, output mechanisms, and valves can be used.

A.3.2.1 HYDRAULIC POWER DRIVE UNITS

The function of a hydraulic power drive unit is to convert hydraulic pressure to a controlled force or torque and hydraulic flow to mechanical motion. Characteristics and applicational merits of the three types listed in Table A-9 are described in the following subsections.

Table A-9. Hydraulic Actuation Concepts

Electrically operated hydraulic control valves	Power drive units	Associated drive mechanisms
• Two-stage electrohydraulic servovalves • Direct-drive, single-stage servovalves • Staged, sequentially controlled valves • Stepper-motor-driven rotary valves • Solenoid valves	Piston actuators	• Direct actuator linear output • Bellcrank or other levers • Rack-and-pinion gearing • Helical spline or ball spline
	Vane actuators	• Direct actuator oscillatory output • Spur gearing
	Multiple-piston motors	• Direct actuator rotary output • Spur gearing • Threaded powerscrew or ballscrew • Planetary or skip-tooth gearing in a hingeline unit

A.3.2.1.1 Piston Actuators

Cylindrical piston actuators are the most popular of the actuator types used for surface control applications and are likely candidates for the 1990s. These actuators can develop very high force outputs and can carry high hinge moments. They have high mechanical efficiency, their motion is easily controlled by the control valve, and they can be designed for use in unbalanced load applications.

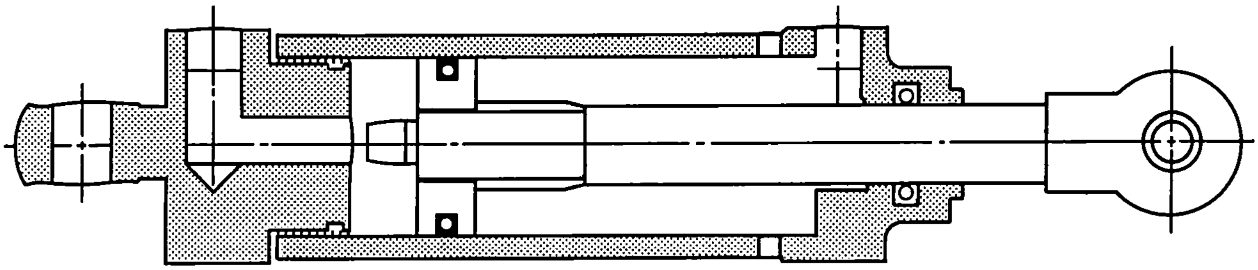
The main disadvantage of piston actuators is that they are difficult to positively lock at other than their stroke extremes. Figure A-16 illustrates typical piston actuator designs.

A.3.2.1.2 Vane Actuators

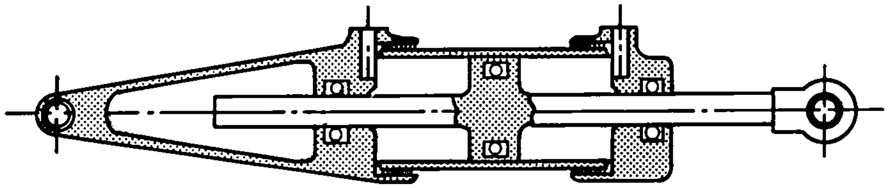
Vane actuators are often considered for applications requiring uniform torque throughout the full range of motion. These actuators have a compact envelope. Their disadvantage is that sealing is difficult between vane units; therefore, they cannot tolerate high hydraulic pressures and would probably be unacceptable for applications requiring a sustained position under high loads. Rudder actuation could be a candidate for rotary vanes, but this is unlikely unless spatial limitations prohibit other designs. Figure A-17 illustrates a typical three-vane rotary actuator.

A.3.2.1.3 Multiple-Piston Motors

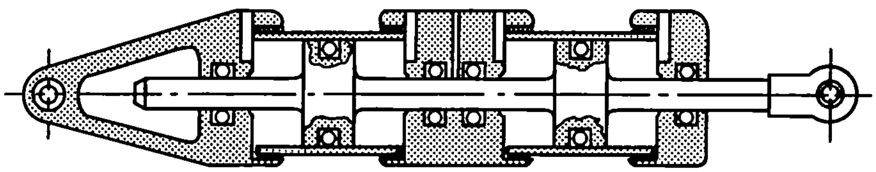
Multiple-piston motors have been used for a number of years to drive electrical generators, fans, and fuel pumps and are being used increasingly for longitudinal trim, flap, and door actuation. These motors can be linked via torque tubes to maintain positive synchronism. Their principal disadvantage is that when large gear reductions are required, overall efficiency is low because of the number of gear boxes required. Multiple-motor systems must also be designed to ensure that a failure (such as a jam) of one motor will not prevent continued operation by the remaining active motors.



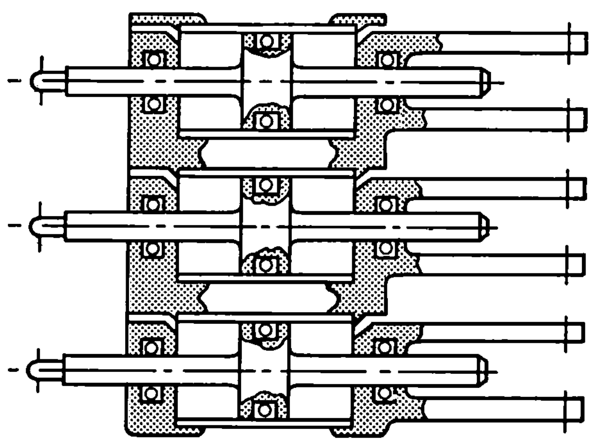
Unbalanced cylindrical piston actuator



Balanced cylindrical piston actuator



Dual-tandem-balanced piston actuator



Parallel-balanced piston actuators

Figure A-16. Piston Actuators

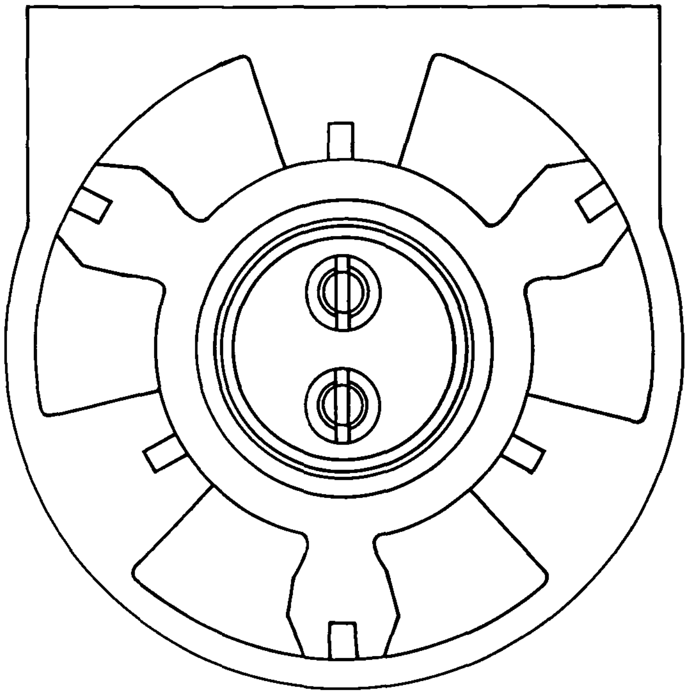


Figure A-17. Three-Vane Actuator

A.3.2.2 HYDRAULIC ACTUATOR CONTROL VALVES

The 1990s commercial transport will be largely fly by wire; thus, a fly-by-wire control system will be required. For this reason, only those valve concepts adaptable to electric command are treated here. If the system should require mechanical or hydraulic primary or backup command techniques, it is likely that there will be little change from those designs currently used.

A.3.2.2.1 Two-Stage Electrohydraulic Servovalves

Two-stage electrohydraulic (EH) servovalves are commonly used for nearly all electrically commanded fly-by-wire actuation systems. Most two-stage EH valves have an electric torque motor controlling the first-stage hydraulic amplifier, which ports fluid to drive the larger (higher hydraulic amplification) second-stage control valve. These EH valves can be used in closed-loop operation of the actuation system by using either electric feedback

from a linear variable-differential transformer transducer, a rotary variable-differential transformer transducer, or mechanical feedback from mechanical motion transmitted to the first-stage torque motor.

A.3.2.2.2 Direct-Drive, Single-Stage Servovalves

The first stage of a conventional two-stage servovalve, which amplifies small torque motor forces by directing hydraulic forces to the main valve spool, has a steady-state fluid leakage that represents a power loss and generation of heat. With increased operating pressures, fluid leakage and power loss would be even higher.

A single-stage servovalve using a high-force, long-stroke electric force motor can drive the main valve spool directly without the fluid leakage and power loss associated with two-stage valves. The designs reviewed to date lack the high-gain chip shearing capability of the pressure-actuated main spool of the two-stage valve.

A.3.2.2.3 Digitally Controlled, Stepper-Motor-Driven Distributor Valves

In the development of a digitally controlled electrohydraulic actuation system using hydraulic motors (ref A-18), it was found that externally commutated hydraulic motors whose pistons are pressurized individually can adapt their flow demands to meet actual power requirements. This is in contrast to most hydraulic motors, whose flow demand is a function of speed regardless of the torque load, therefore allowing a considerable reduction in the maximum flow requirement in applications where maximum rate is required at low load conditions. Such a system uses a rotary distributor valve controlled by a suitable electric stepper motor (fig. A-18) and a rotary encoder feedback transducer. An additional advantage of this arrangement is that for some applications it can be operated in an open loop following a feedback failure, for example, and be less prone to a hardover surface failure.

Theoretical predictions indicate that a reduction in flow demand approaching 75% of the flow rate required for a normal fixed-displacement motor operating at high speed and low load could be obtained. In reality, tests to date of a prototype unit indicate that leakage and other losses will prevent achieving this hypothetical reduction. A 50% reduction is a more likely figure; and until better data become available, that reduction will be assumed.

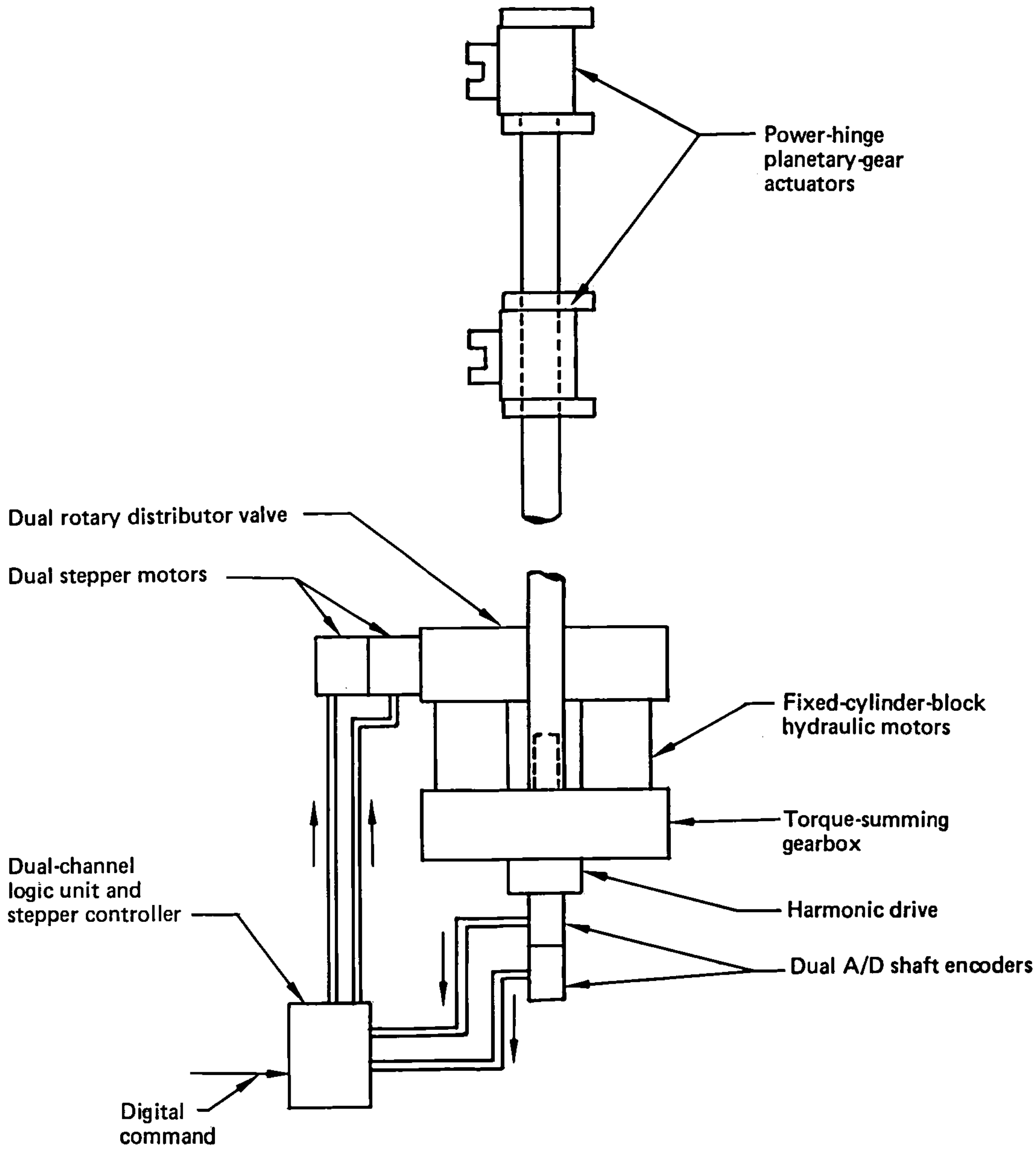


Figure A-18. Digital Electrohydraulic Motor Actuation System With Rotary Distributor Valve

With that assumption, it is possible to predict approximately equal design flow rates for hydraulic-motor-driven hingeline gearbox systems and cylindrical piston actuators. The increase in flow required by the relatively low efficiency of the hingeline gearbox system is compensated by the 50% reduction in flow demanded by the externally commutated motors at the high-speed, low-load condition.

A.3.2.2.4 Staged, Sequentially Controlled Valves

An alternative scheme has been conceived to sequentially control multiple hydraulic ram actuators so that they can adapt their power demands to meet the existing magnitude of resisting loads and also to recover power from aiding loads. This scheme, shown in Figure A-19, uses a series of conventional hydraulic servoactuator cylinders arranged either in parallel or in tandem. The only modification is in the control valves and in the addition of hydraulic accumulators.

The control valves (fig. A-20) are designed so that, under light loads, only one of the actuators is pressurized to carry the load while the others are bypassing fluid from one cylinder port to the other. When the load increases to the point where the first actuator can no longer carry it alone, the second actuator is pressurized and acts to control surface position by drawing flow from the pressure line in the normal manner. The first actuator remains pressurized and continues to push with maximum force, but motion of the piston simply exchanges fluid from pressure and return lines to the pressure and return sides of the cylinder.

As each actuator reaches its maximum output capability, the next actuator begins to modulate its output force and becomes the controlling actuator, with the former actuators acting as constant-force output devices (zero-rate springs). Only the controlling actuator draws fluid from the supply pump; the others draw fluid from local pressure-line accumulators. As the valve on the actuator that is in control allows the set of actuators to retreat from the load, fluid from the actuators that had previously stalled will be pumped back and stored in the pressure-line accumulators with the other side of their pistons being filled from the return line. When the set of actuators again moves against the resisting load, fluid for the stalled actuators is supplied by the accumulators; and the fluid demand on the supply pump is only that amount demanded by the actuator in control. Thus, the demand from the supply pump is directly reduced by the number of

actuators in the group. With two actuators, the maximum demand from the supply system is one-half that for a normal arrangement. With three actuators, it is one-third; and with four actuators, it is only one-fourth of the demand for a normal arrangement.

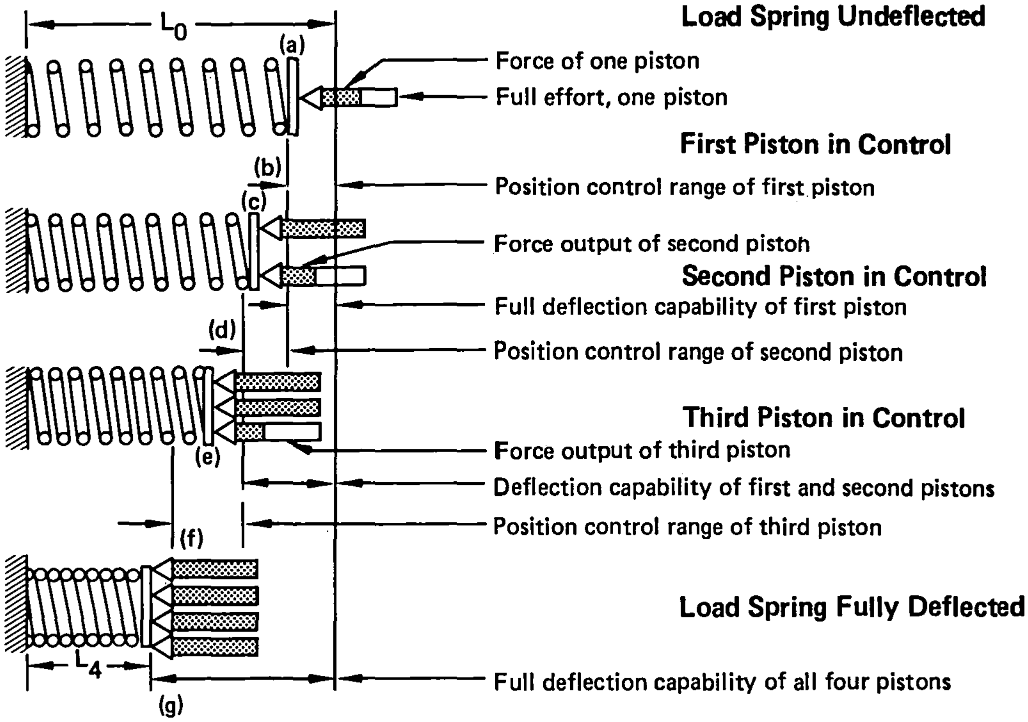


Figure A-19. Staged, Sequentially Controlled Actuation Scheme

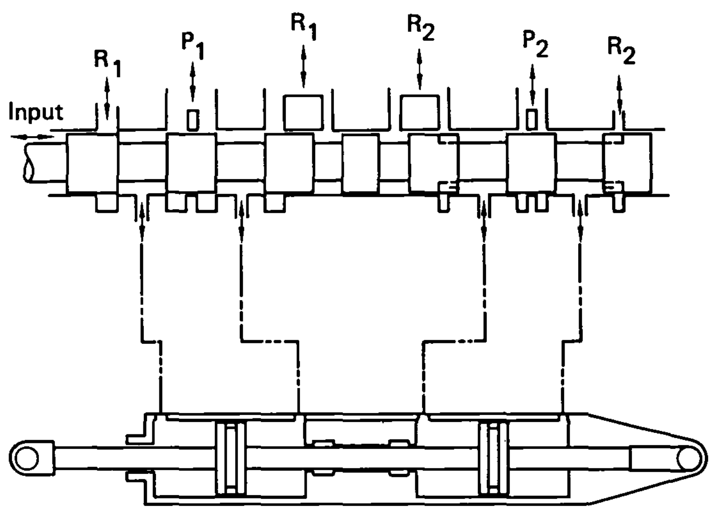


Figure A-20. Staged, Sequential, Servo Ram Actuation Scheme Applied to a Dual-Tandem Servoactuator

A.3.3 ELECTRIC ACTUATOR COMPONENTS

In this assessment, electric actuator concepts are considered to be electrically controlled actuator systems that transmit power without the use of hydraulic lines. The two systems to be discussed are (1) the electromechanical actuator (EMA), which uses direct electrical-to-mechanical conversions and (2) the integrated actuator package (IAP), whereby electric power is converted to hydraulic power at the actuators.

A.3.3.1 ELECTROMECHANICAL ACTUATION

Three EMA concepts have been reviewed for this assessment: (1) direct-drive servo motor—gearbox actuation control, (2) clutched electric actuation control, and (3) mechanical servo power package. The following subsections describe each concept.

A.3.3.1.1 Direct-Drive Servo Motor—Gearbox

Figure A-21 illustrates a typical direct-drive servomotor EMA. The controller-inverter controls and transmits electric power to the drive motor. Drive-motor speed is generally high and speed reduction is required. Motor selection is an important part of the EMA actuation system. The most likely candidate for primary flight control applications is the brushless, dc, permanent-magnet motor using rare earth magnets in the motor for fast response and high operating efficiency. Figure A-22 shows a typical horsepower versus weight curve for a 20 000-r/min samarium-cobalt dc motor.

A.3.3.1.2 Clutched Electric Actuation

Figure A-23 illustrates a clutched electric actuation system whereby the drive motor runs continuously in one direction and the clutches cause the output shaft to run clockwise, counterclockwise, or to remain fixed. Because the motor runs continuously, motor inertia can provide a stored energy source for high peak power requirements. Thus, the motor might be sized around low-level, rather than peak, power requirements (see ref A-18 for assessment of other clutch types).

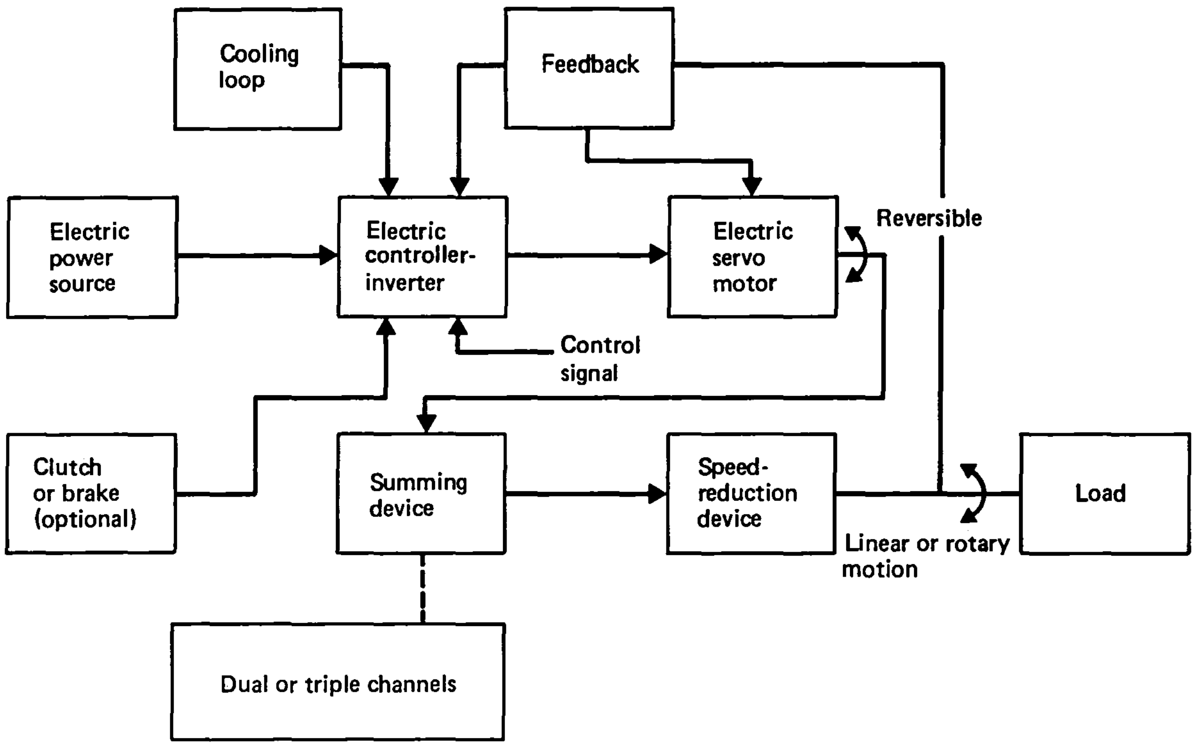


Figure A-21. Direct-Drive Servo Motor—Gearbox

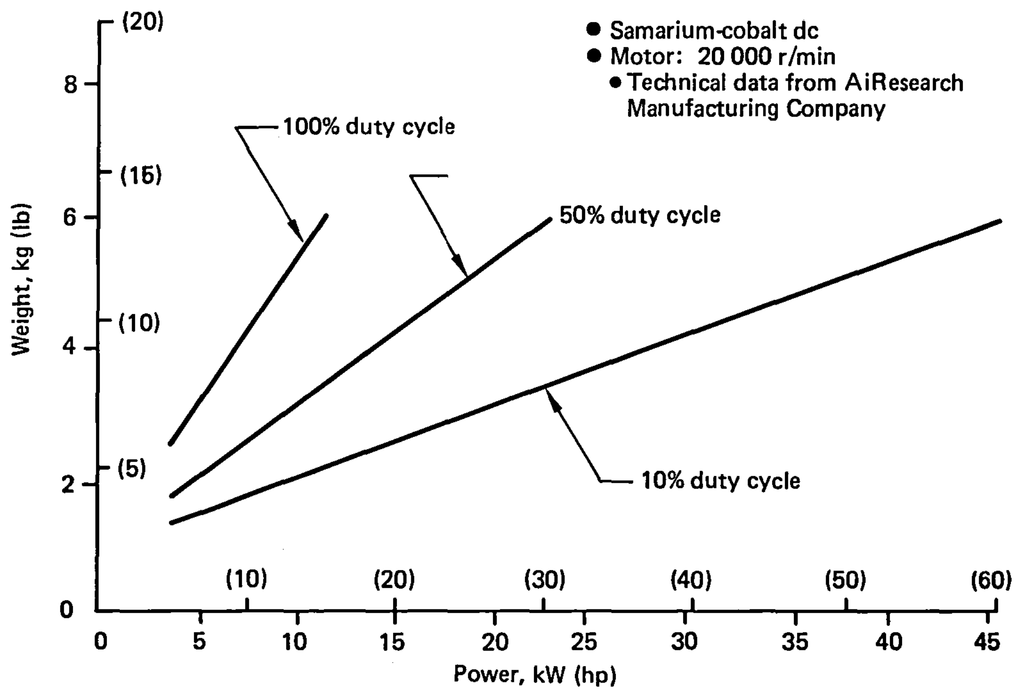


Figure A-22. Motor Horsepower Versus Weight

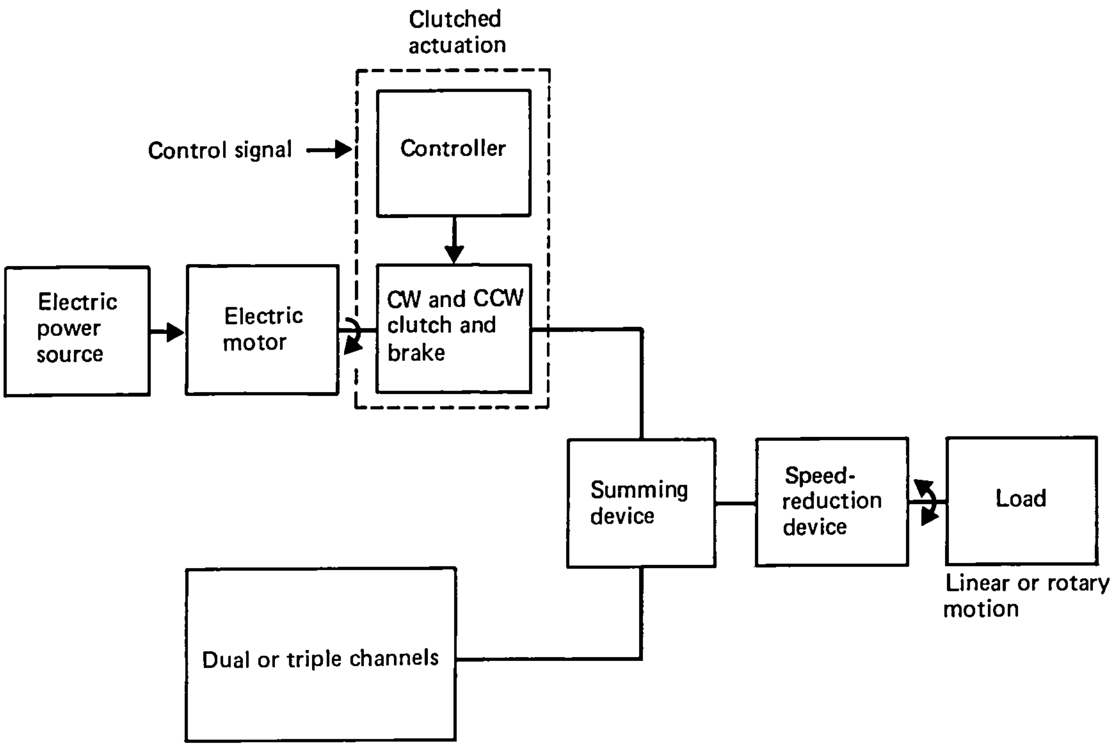


Figure A-23. Clutched Electric Actuation Power Package

A.3.3.1.3 Mechanical Servo Power Package

Figure A-24 shows another actuator concept using a unidirectional drive motor. This system uses a flywheel for energy storage and therefore can be sized to meet only the average load requirements. A mechanical controller (fig. A-25) provides an infinitely variable bidirectional output. This concept, developed by Rockwell International Corporation, could offer power savings over the direct-drive system for applications that do not require holding high sustained loads.

A.3.4 INTEGRATED ACTUATOR PACKAGE ACTUATION

Three IAP concepts, integrating an electric-driven hydraulic pump and necessary accessories into one package, are (1) servo pump, (2) valve accumulator, and (3) fixed-displacement pump. Because these actuators are built into a self-contained, compact unit, maintenance can be done in the shop, improving maintenance cost and dispatch.

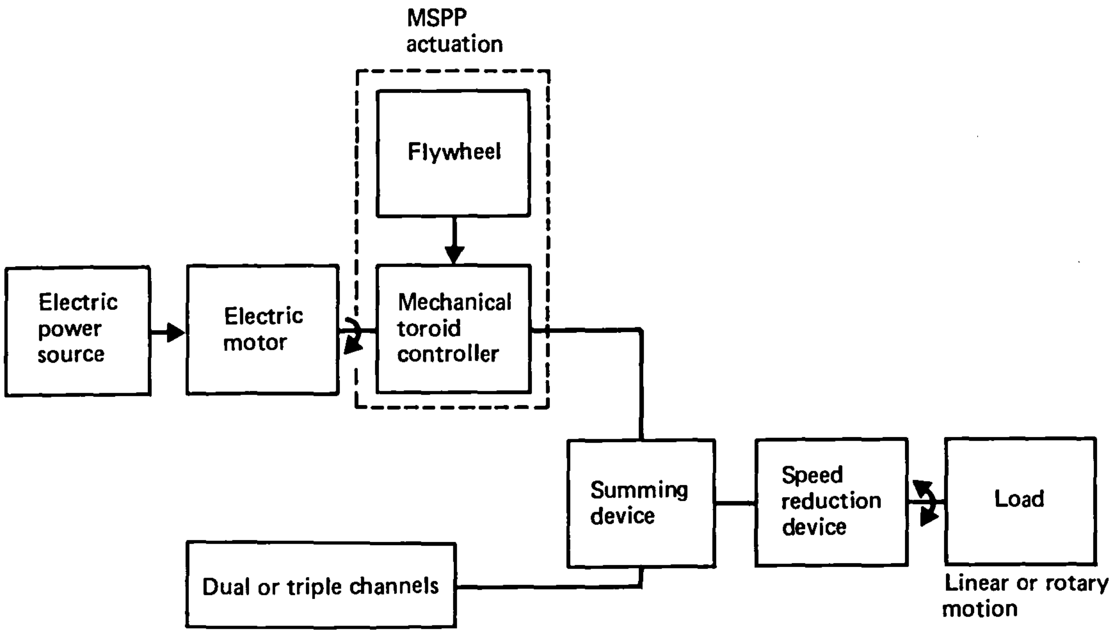


Figure A-24. Mechanical Servo Power Package

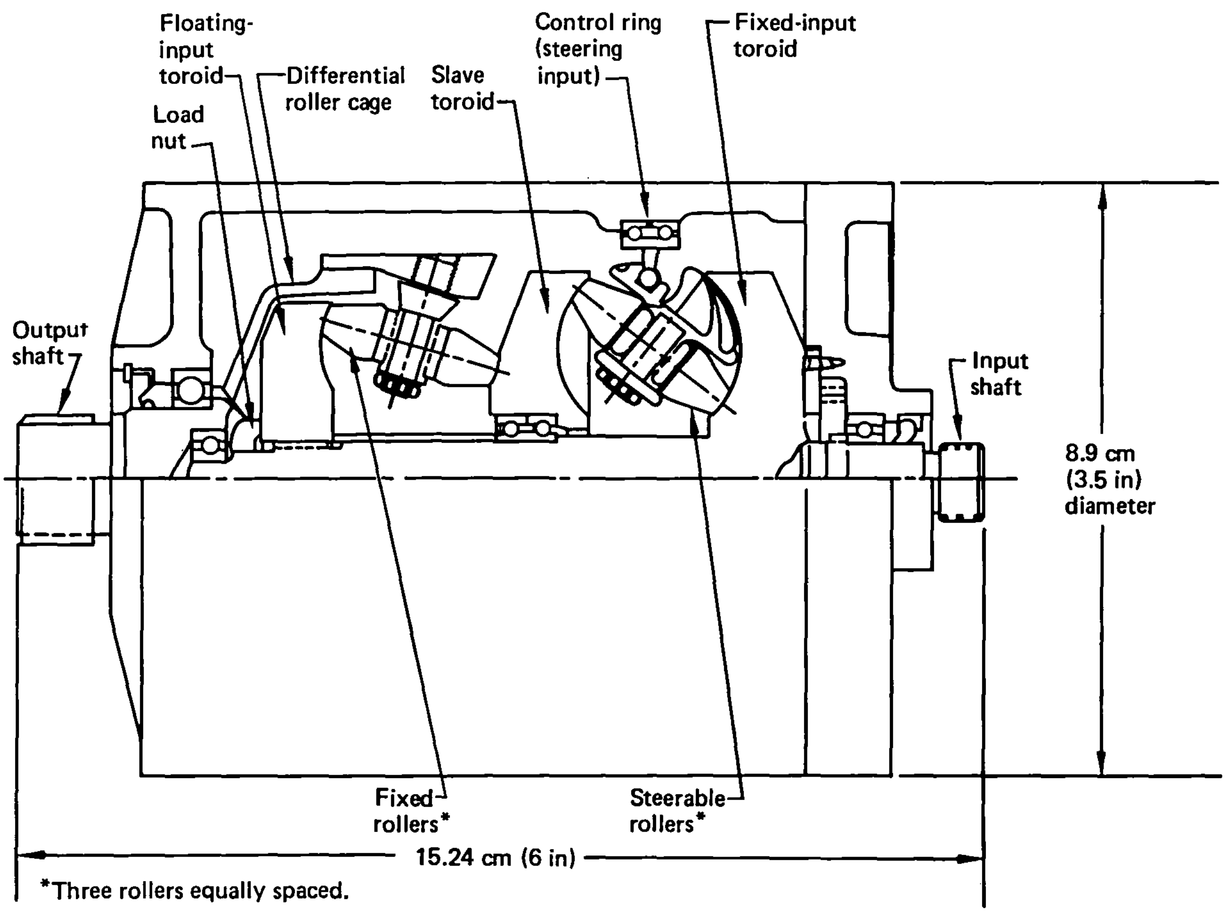


Figure A-25. Mechanical Servo

A.3.4.1 SERVO PUMP IAP

The servo pump IAP uses a bidirectional pump coupled directly to the actuator with hydraulic fluid flow proportional to the input signal. Thus, the hydraulic pressure level is adjusted in accordance with load demand, reducing heat generation and power consumption. ABEX and Vickers servo pump concepts are shown in Figures A-26 and A-27, respectively.

A.3.4.2 VALVE ACCUMULATOR IAP

The valve accumulator IAP uses an energy storage device to meet peak flow demands, thus permitting the system to be designed to the average demand. Some of the problems normally associated with pressure accumulators; namely, their large size and complexity, have been overcome with a design concept known as the constant-pressure hydraulic accumulator (fig. A-26). Using low-pressure (less than 1030 kPa (150 lb/in^2)) fluid to augment the high-pressure gas force, a relatively constant pressure is achieved. Also, a high percentage (about 50%) of the total energy stored is available for use, compared to other systems.

A.3.4.3 FIXED-DISPLACEMENT PUMP IAP

The fixed-displacement pump IAP is a concept that is similar to the electromechanical actuator. The major difference is that speed reduction devices of the EMA are replaced by a hydraulic pump and hydraulic actuator. Figure A-27 illustrates the concept.

A.3.5 ACTUATOR TECHNOLOGY FORECAST CONCLUSIONS

Active controls, especially in high-performance military aircraft, are beginning to push actuator technology, especially where benefits can be realized in reduced weight and improved reliability. In the near term, commercial transport designers will usually use more-or-less conventional hydraulic systems for flight-crucial controls. But all-electric control functions have been used on current new-generation commercial transports; e.g., the Boeing 757 is planning to use a full-authority electronic engine control on the Pratt & Whitney 2037 engine, with no mechanical or hydraulic system backup. All-electric surface control actuators are probably not practical to use on current new-generation

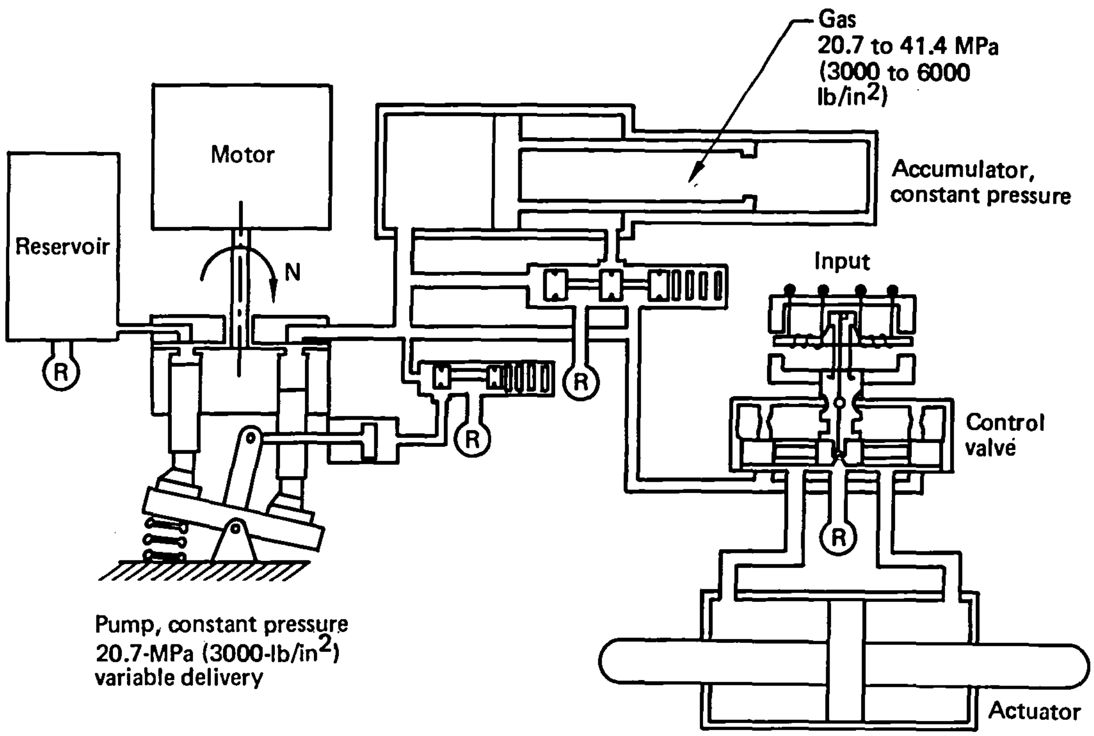


Figure A-26. Servovalve and Accumulator Integrated Actuator Package Schematic

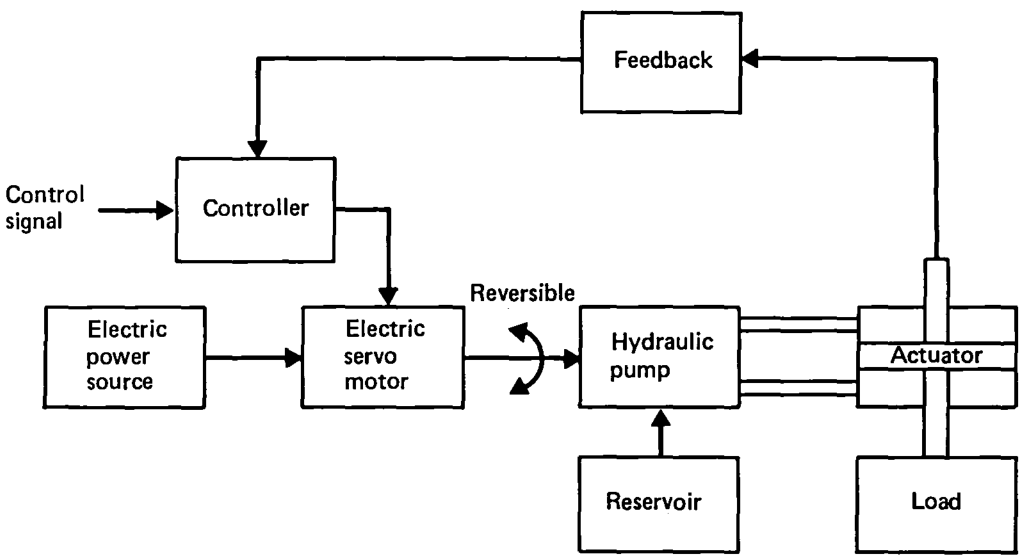


Figure A-27. Fixed-Displacement Pump, Integrated Actuator Package

transports because the technology is not yet sufficiently mature. However, there is little question that most or all of the problems in the preceding systems will be resolved within the 1980s. Airplane actuator technological development is focused on achieving benefits in weight, design flexibility, reliability, and maintainability. Some of these technology objectives could result from efforts outside the aircraft industry; e.g., as industries (such as automobile manufacturing) become more automated, reliability of the robotized production lines will become an important consideration and there will be more incentive to develop improved actuator components.

Another manufacturing industry incentive to improve motors and controllers is efficiency improvement. A study (ref A-19) sponsored by the Federal Energy Administration (FEA) concluded that 26% of the total electric energy produced in the United States was consumed by motors of 746W to 93 kW (1 to 125 hp). The potential for energy (and therefore cost) savings is enormous. Using developing motor and motor controller technology, A. D. Little, the FEA study contractor, estimates a savings equivalent to 60 million barrels of oil, or $2 billion (1981 dollars) per year by 1990. The aircraft industry will benefit from such developments.

Currently, on a system component basis, electric actuators still weigh from 10% to 30% more than their hydromechanical counterparts. When the hydraulic power and distribution system is included, a closer weight parity may be achieved. As developments in load-adaptive actuators evolve (both electric and hydraulic), significant weight reductions will be achieved. The principal benefits expected from electric actuation systems will be design flexibility and simplified maintenance. IAPs and electromechanical actuators are expected to compete with hydraulics in the 1990s for commercial transport applications.

A.4.0 FLIGHT DECK CONTROLS AND DISPLAYS

This section covers the control and display developments in process and projects the usability of these developments to the 1990s generation of commercial transport airplanes.

A.4.1 CREW STATION DISPLAY REQUIREMENTS

The requirements for operational and physical characteristics of crew station displays are described in the following subsections. Table A-10 compares the characteristics and merits of the important display types.

Table A-10. Display Technology Comparison Matrix

Display type	Operating principle	Common panel size, cm (in)	Maximum average luminance, cd/m^2 (fL) unfiltered	Gray scale at 108 000 lx (10 000 fc) ambient	Contrast ratio at 108 000 lx (10 000 fc) ambient
CRT	• Shadow mask • Hybrid scan • Triad phosphors	Usable area 13 x 18, 36 deep (5 x 7, 14 deep)	• 340 to 3400 (100 to 1000) (red to green)	• 6 to 8	• 4:1 color • 12:1 monochromatic
EL (thin film)	• Vacuum film deposit (ZnS) • Photon emission	13 x 15, < 2.5 deep (5 x 6, < 1.0 deep)	• 140 (40)	• 2 • 16 predicted	• 1.5:1 • 10:1 predicted
LC	• Reflective • Transmissive	Modular, 9 x 9, < 2.5 deep (3.5 x 3.5, < 1.0 deep)	• N/A–illumination dependent	• 8 to 10	• 20:1 at 60°C (+140°F) • 2:1 at 0°C (+32°F)
LED	• Forward-biased PN junction • GaP, GaAs, or GaAsP substrate	Modular, 13 x 10, < 2.5 deep (5 x 4, < 1.0 deep)	• 700 to 1030 (200 to 300)	• 4 to 6	• 6:1
Plasma (ac and dc)	• Gas discharge	21.5 x 21.5, < 2.5 deep (8.5 x 8.5, < 1.0 deep)	• ac: 70 to 170 (20 to 50) • dc: 0 to 170 (0 to 50) • Color: 70 (20) (peak)	• ac: 2 (bistable) • dc: Full gray scale	• 1.6:1

Table A-10. Display Technology Comparison Matrix (Continued)

Display type	Colors	Resolution dot triads per cm (in)	Refresh requirements	Rise or fall time	Operating temperature range, °C (°F)
CRT	• > 20 (varies with phosphor type)	• 32 (80)	• 50 to 80 Hz typical (varies with phosphor type) • 50 stroke • 40/80 raster	0.2 μs to 1 ms (depends on phosphor type)	-20 to +70 (-4 to +158)
EL (thin film)	• 2 to 3 (blue-green-yellow) • Full-color predicted	• 20 (50) • 26 to 80 (65 to 200) predicted	• 60 to 250 Hz	2 μs to 1 ms	-40 to +100 (-40 to +212)
LC	• 1 normally (W on B) • 3 predicted (red-green-yellow)	• 40 (100) reflective • 24 (60) trans-missive	• Slow (TV rate blurred)	10 ms to 1 sec	-10 to +60 (+14 to +140)
LED	• 4 (red-orange-yellow-green) • Full-color (red-green-blue) predicted	• 25 (64) mono-chromatic • Red-green pairs, 9/cm (23/in)	• Very high (500 Hz typical)	10 ns	-40 to +70 (-40 to +158)
Plasma (ac and dc)	• 1 neon orange (DIGIVUE) • Full color using UV predicted	• 24 to 35 (60 to 88)	• ac: None required (bistable)	20 μs	-60 to +60 (-76 to +140)

Table A-10. Display Technology Comparison Matrix (Continued)

Display type	Voltage and power requirements	Luminous efficiency, lm/W	Inherent memory	Dominant wavelength, nm	MTBF (high ambient), hr	Cost, $
CRT	• > 18 kV, 100W to 150W, 0.78 W/cm^2 (5 W/in^2) typical	• 0.1 to 65 (20 typical)	• None	Varies with phosphor type	• 3000 to 5000 • 10 000 anticipated	• 4700–commercial quality • 15 750–flight quality (Collins)
EL (thin film)	• 30V to 650V ac, 25W, 0.125 W/cm^2 (0.8 W/in^2) typical	• 2 to 5 (typical) • 10 predicted	• None	525 to 585	• 10 000 • 20 000 reported	• 3500 to 5000–nonflight quality • Single color
LC	• 2V to 35V dc, 1W to 4W, 0.016 W/cm^2 (0.1 W/in^2) reflective, 0.047 W/cm^2 (0.3 W/in^2) transmissive	• N/A	• Yes	Varies	• 10 000 • > 20 000 anticipated	• Unknown–no large panels made to date
LED	• 1.5V to 5.0V dc, 3 W/cm^2 (20 W/in^2) typical	• 0.5 (typical)	• None (fast rise and fall time)	470 to 650 (red-orange-yellow-green-blue)	• 10 000 • 25 000 anticipated	• 6500–nonflight quality • Single color • 620/cm^2 (4000/in^2) with drivers
Plasma (ac and dc)	• 140V ac or dc (sustaining) • 200V ac or dc (firing) • 200W to 250W, 0.47 W/cm^2 (3 W/in^2) typical	• 0.3 (DIGIVUE)	• ac: Yes • dc: No	585 (neon)	• 10 000 to 100 000	• 4000 to 9500–nonflight quality • Single color

Table A-10. Display Technology Comparison Matrix (Concluded)

Display type	Readability (high/dark ambient)	Viewing angle, deg	Device uses recommended for 1980 and predicted 1990	Advantages and disadvantages
CRT	Excellent	±80	• Video • Graphics • Messages • Discretes	• Highly flexible with color • Good contrast • Easily addressable • Environment resistance • Cost reasonable
	Excellent		• Predicted— same as above	• High voltage • Depth problem, 30.5 to 36 cm (12 to 14 in) deep • Implosion risk • Color registration problem, large CRT
EL (thin film)	Marginal	±90 (lambertian)	• Messages • Discretes	• Thin panel and rugged • Good resolution predicted • Excellent viewing angle • Excellent temperature range • Low power requirements
	Excellent		• Predicted— • Video • Graphics • Messages • Discretes	• Low gray scales for TV • Poor image quality • Complex addressing (high voltage)
LC	Excellent	±15 to ±40	• Messages • Discretes	• Thin panel and rugged • Low power and long life • Excellent contrast under direct sunlight • High reliability and long life
	Poor		• Predicted— • Graphics • Messages • Discretes	• Viewing angle and temperature problems • Small panels, 11.3-cm^2 (1.75-in^2) modules • Slow rise or fall for TV • Needs external light at night
LED	Good	±45	• Graphics • Messages • Discretes	• Thin panel and rugged • High brightness • Good contrast • Excellent temperature range • Full color range
	Good		• Predicted— • Graphics • Messages • Discretes	• High power consumption—may require external cooling • High refresh rate required • Viewing angle problem • Expensive
Plasma (ac and dc)	Marginal	±70	• Graphics • Messages • Discretes	• Thin panel and rugged • Bistable—requires no refresh
	Poor		• Predicted— • Graphics • Messages • Discretes	• Low contrast • Lacks gray scale for video (bistable) • Neon orange unacceptable • Pressurization problems above 6550m (20 000-ft) altitude • Complex addressing (high voltage)

A.4.1.1 READABILITY

The display symbology should be clearly readable under all ambient lighting levels ranging from nighttime conditions up to and including an illumination of 86 400 lx (8000 fc) at a 45-deg incidence to the face of the display (ref A-20).

A.4.1.2 VIEWING ANGLE

For commercial cockpits, the angle-of-view ability of a display should be unlimited; however, at least 53 deg left and right, 35 deg above, and 0 deg below without intolerable parallax or loss of display image contrast is required (ref A-20).

A.4.1.3 CONTRAST RATIO

Contrast ratio (CR), sometimes referred to as simply contrast, is a basic parameter in evaluating the quality of a display. CR is a function of display brightness and background luminance. Specifications for head-down displays call for CRs of 7:1, under a 108 000-lx (10 000-fc) ambient. For head-up displays, a minimum CR is generally expressed as a ratio of 1.2:1.

A.4.1.4 RESOLUTION

Resolution is defined as the smallest discernible or measurable detail in a visual presentation. This definition is based on the physiology of the eye. The foveal acuity of the eye is such that the smallest element discernible is 1 min of arc of visual angle. At a cockpit viewing distance of 71 cm (28 in), this "spot" would be 0.2 mm (0.008 in) at its smallest dimension, which is 50 lines/cm (125 lines/in).

In cathode-ray tube (CRT) displays, resolution is generally expressed in terms of lines of display resolution (525, 875, and 1000 lines) over the face of the display. For the 1990 crew station, the CRT should support an 875-line TV format. A minimum design goal is a 800-line vertical and 1000-line horizontal format.

In flat panel displays, the terms most frequently used are linear density, pixels per line per centimeter (inch), and total number of elements (256 x 408 display). To be

comparable with a TV 875-line format on a 19- by 25.5-cm (7.5- by 10-in) display, dot matrix displays should have a minimum of 47 (120) pixels per line per centimeter (inch), which also happens to be the smallest detail the eye can resolve at a 71-cm (28-in) viewing distance.

A.4.1.5 GREY SCALE

Grey scale is the number of shades of grey between the brightest and darkest elements taken in two increments of intensity. For cockpit displays (EADI and EHSIs), the literature calls for 8 to 10 grey shades for sensor video.

A.4.1.6 COLOR CAPABILITY

Color will be required for displays in the future. Color was first introduced to cockpit displays in the military with the use of beam penetration tubes, which produced four distinct colors (red-yellow-amber-green). Later introduction of shadow-mask displays for commercial transports (757/767) has opened new opportunities for color. The shadow-mask CRT can produce many discriminable colors (20); however, recent studies have shown that a relatively small number of colors (three to six) should be used (refs A-21 through A-24). For the 1990 cockpit, the display should be capable of displaying a minimum of seven colors (red, amber, yellow, blue, green, magenta, and cyan) plus white, even though perhaps only three to six would be used at one time.

A.4.1.7 ANTIREFLECTION COATING

The viewable surface of the display should be treated with an appropriate antireflection (AR) coating. The average reflectance of AR coating is typically 0.25%. For example, if the ambient luminance from a white cloud bank is 108 000 lx (10 000 fc), which is incident on a display surface, the luminance of the reflected light would be 85 cd/m^2 (25 fL). Installation of a display should avoid a condition where the direct sun is reflected from the AR coating. The luminance of the sun is several million lux, and even though the reflectance of the coating is extremely low, the resulting reflection can wash out a display.

A.4.1.8 REFRESH RATE

The length of time that imagery remains visible on the display is a function of display persistence. A few display applications require short persistence times, but most require more persistence than the display material can provide, so the display must be repeated or refreshed to avoid flicker. This takes time and power and increases the complexity of the display-drive electronics. Obviously, the rate of refresh depends on persistence or inherent memory of the device, whether it is a CRT or a flat panel type using a different operating principle.

Refresh rates for CRTs should not be less than 50 Hz for a stroke-written display and a frame/field rate of 40/80 Hz for a 2:1 interlace raster scan (ref A-20). Refresh rates for flat panel displays will vary according to the phosphor or substrate used and may vary from 0 to 500 Hz.

A.4.1.9 FORM FACTOR

The trend for future transports is toward larger displays, depending on the sensor data to be displayed (TV, forward-looking infrared radar, or radar). Based on the relationship between a viewing distance of 61 to 76 cm (24 to 30 in) and 800 to 1000 lines of imaging resolution, the largest recommended display is 19 by 25.5 cm (7.5 by 10 in). However, installation constraints (form factor) may be a deciding factor in selecting the size of the display. Most cockpits today do not tolerate more than a 23-cm (9-in) diagonal CRT, approximately 14 by 18 cm (5.5 by 7 in).

Display depth available in the cockpit has been under investigation for many years. Electromechanical instruments have become long cylinders, with large length-to-diameter ratios, further complicating their design, fabrication, and maintenance. Present-day cockpits permit primary flight instrument depths to 35.5 cm (14 in), plus space for connectors, and this will probably not change for future transports.

For flat panel displays, depth required for engine and system displays on the center main instrument panel in 1990 will be considerably less than that for the CRT flight instrument displays. Additional space will become available behind the panel in which to install head-up display (HUD) electronics and relay optics. A holographic combiner can be located

near or actually on the windscreen. Therefore, depth for these displays (engine and system) should be no greater than 5 to 10 cm (2 to 4 in) to provide space for the HUD projection optics.

A.4.1.10 POWER REQUIREMENTS

Power requirements for aircraft displays are important because of the cost. Also, the cooling power to neutralize the heat generated by the displays must be considered. When possible, units should be designed to use 115V, 400-Hz, single-phase power from a system designed for Category A utilization equipment per ARINC 413A.

A.4.1.11 OPERATING TEMPERATURE RANGE

Some displays produce excessive heat, which loads both avionics and crew air-conditioning. Also, the physical properties of some display materials are functions of temperature. A selected display must be heated or cooled as necessary to permit its function. Commercial standards set the requirements for acceptability from -15^{o} to +70^{o}C (+4^{o} to +158^{o}F).

A.4.1.12 SHOCK AND VIBRATION

Shock and vibration are important design considerations, as attested to by the rigorous acceptance testing found in the commercial environmental standard, DO-160. When considering color CRTs, the shadow-mask physical size is limited to that where misregistration of colors becomes a problem during shock and vibration.

A.4.2 CATHODE-RAY TUBES

Problems with CRTs are form factor, hazards, and reliability. Depths of CRTs for flight hardware can be as much as 46 cm (18 in), depending on its application. As a general rule, the depth will be approximately 1.2 times the diagonal of the CRT. There is a danger or risk from implosion of the tube, as well as high-voltage shock. Potentially dangerous X-ray radiation also exists without special shielding.

Reliability numbers for most CRTs depend on the application and the data source. One author (ref A-25) believes a 15 000-hr mean time between failures (MTBF) for a typical avionic CRT is being achieved, but points out that CRTs for HUDs, which must be driven to about 35 000- to 50 000-cd/m^2 (10 000- to 15 000-fL) phosphor brightness with slow writing speeds, rarely achieve more than a 1000-hr MTBF. Predicted MTBFs for Collins color displays for the 757/767 range from 5000 to 7000 hr. Therefore, a figure of 3000 to 5000 hr is reasonable now and remains an advantage over electromechanical displays with 700- to 800-hr MTBFs. MTBFs of 10 000 hr for color CRTs are predicted for future applications.

In spite of several undesirable characteristics, the CRT has dominated the market for over 40 years and is chosen for numerous applications because of its tremendous format flexibility. CRTs are available in a variety of sizes and shapes, provide grey scale and color, have reasonably good resolution, can provide a storage capability, and can be addressed with both raster and stroke patterns (ref A-26).

A.4.3 FLAT PANEL TECHNOLOGY

Many flat panel technologies are currently in some stage of development, including:

- Electroluminescence (EL)
- Liquid crystals (LC)
- Light-emitting diodes (LED)
- Plasma
- Electrochromic
- Electrophoretic
- Magnetic particle

Other flat panel devices, such as vacuum fluorescent displays and flat CRT display (DIGISPLAY), have some merit. The four most promising technologies are described in the following subsections.

A.4.3.1 ELECTROLUMINESCENCE

Some of the general problem areas of flat panel displays are low luminous efficiency, color limitations, lack of uniformity and grey scale, high-voltage drivers for addressing, and cost (ref A-26). Electroluminescent panels have most of these problems, as well as certain advantages. Some advantages are higher luminous efficiency than other flat panel technologies, excellent viewing angle, good temperature range, excellent color range, and low power.

Luminous efficiency is an excellent parameter for assessing the practicality and future of flat panel technology (ref A-27). With a desired goal of video efficiency in the 1- to 2-lm/W range, EL has efficiency now at 2 to 5 lm/W with predicted improvement of 5 to 19 lm/W (refs A-26 and A-28). Presently, the EL panel is marginal for high ambient applications, but has been demonstrated in less-demanding home-TV applications (ref A-27).

Full color is attainable. Industry to date has demonstrated ac thin-film EL emissions in red, blue, white, and yellow (ref A-29). EL powder displays have produced colors ranging from green to blue and from red to blue. The most commonly used EL powder is copper-

activated zinc sulfide (ZnS:Cu), which produces green to blue (ref A-26). The most commonly used ac thin-film phosphor is manganese-activated zinc sulfide (ZnS:Mn), which produces an orange-yellow color.

High-voltage drivers are a problem for EL displays because the brightness of the EL display is directly related to the applied voltage across the phosphor layer; this voltage ranges from 80V to 300V, depending on display material and design. Several schemes are under way to reduce the voltage, primarily in construction of the thin-film device itself.

As with all flat panel devices, nonuniformities are a problem. Small area discontinuities consist of failed pixels, or a failure in addressing line drivers can cause a complete line of pixels to be inoperative. Most of these problems are gradually being solved and in all probability will be resolved by 1990.

A.4.3.2 LIQUID CRYSTAL

Some salient features and problems are summarized. Advantages for LCs are excellent contrast and grey shades even in direct sunlight, good predicted resolution, low voltage, and high reliability. Some disadvantages are small viewing angle and temperature problems, slow rise and fall times for video applications, and size of the display available.

LCs are passive devices using electro-optic materials to modulate ambient light. Such displays depend on the light-scattering properties of nematic LCs. The LC material flows like a viscous fluid but has an ordered orientation of its molecules like a crystal (ref A-30). Unfortunately, the viscosity of the LC, which permits the desired electro-optic effect, is temperature dependent. The useful range is between -10° to $+60^{\circ}$C ($+14^{\circ}$ to 140°F). At -10°C ($+14^{\circ}$F), typical response time is 1 sec—much too slow for video, graphics, or alphanumeric messages. There is no known solution for this problem, except to provide heating (ref A-30).

Viewing angles limited to ± 45 deg present a cross-vision problem for the crew, and also reduced contrast ratio at the larger angles. The result is that as viewing angle increases from 0 deg, the useful contrast on the display is lost at something less than 45 deg (refs

A-31 and A-32). In a wide-body commercial cockpit, the pilots would not be able to read each other's panel instruments, as well as some of the displays and instruments on the center instrument panel.

Current LC panels are small. LCs that have demonstrated a video capability (within the higher temperature range) have been fabricated with silicon MOS technology and have attained a size of 9 by 9 cm (3.5 by 3.5 in). The display is made of four edge-abutted 4.5- by 4.5-cm (1.75- by 1.75-in) matrix modules. Another approach that appears to have considerable merit is thin-film technology (TFT) addressing and controlling matrix to drive an LC panel (ref A-33).

A 15- by 15-cm (6- by 6-in), 12-lines/cm (30-lines/in) TFT addressed-LC display panel has been demonstrated with video imagery. The panel was refreshed at 60 frames/sec. A contrast ratio of 28:1 was recorded. Also, a maximum of eight grey scales was achieved. However, the rise time response was 20 ms and the decay response time was 25 ms, much too slow for imagery, but probably would be adequate for graphics, messages, and discretes.

A.4.3.3 LIGHT-EMITTING DIODE

LEDs for use in primary flight instrument displays are not acceptable at their current state of development. The basic disadvantage of LEDs is in the luminous efficiency, which is somewhere between 0.06 and 0.5 lm/W (ref A-27). Greater efficiencies have been found in red-emitting LEDs, but established convention for the use of color coding mitigates against red for EADI and EHSI applications.

Power efficiency is another drawback for LEDs. If a display of LEDs having efficiencies of 0.1 lm/W was built with 512 by 512 pixels in a 30- by 30-cm (12- by 12-in) display and operated at 350-cd/m^2 (100-fL) average brightness, the power dissipated in the line drivers and panel would be 1000W (ref A-27).

Other problems with an LED application in a video-quality display module include limited viewing angle (± 45 deg), high cost, uniformity, addressing, and availability of color. Several available colors cannot meet brightness requirements in high ambient light conditions, particularly blue.

Probably the most promising area for LEDs is the role as matrix readout devices for multifunction keyboards (MFK), which are described in Subsection A.4.4. Another use is in the Traffic Alert and Collision Avoidance System (TCAS) display. TCAS displays can be rather small, 38- by 76- by 19-mm-deep (1.5- by 3- by 0.75-in) modules, in tricolor, at a resolution of 9 (22) pixel pairs/cm (in) (red and green).

A.4.3.4 PLASMA

In the non-CRT commercial market, plasma panels are widely used as alphanumeric displays. In a 20- by 20-cm (8- by 8-in) panel known under the trade name of DIGIVUE, some salient features are resolution of 24 dots/cm (60 dots/in), 70-deg viewing angle, inherent memory (bistable), 0.62-W/cm^2 (4-W/in^2) power, panel life of over 20 000 hr, and it is ruggedized.

On the surface, the characteristics appear to meet requirements for flat panel displays; but for use in pilot instruments, the panel is unacceptable. Until recently, the only color available was neon-orange, not only a disagreeable color but in conflict with caution and warning coding.

Recently, a green-emitting gas-discharge display has been developed, but its brightness is poorer than the neon-orange display, which typically exhibits only 70 to 100 cd/m^2 (20 to 30 fL). A breakthrough in color phosphor deposition is needed before acceptance. Existing technology does not allow use at either high or low ambient light conditions. Although capable of surviving atmospheric pressure up to 21 000m (70 000 ft) in a nonoperating environment, the operating limit is 6100m (20 000 ft).

A.4.4 MULTIFUNCTION KEYBOARD CONTROLS

An MFK is the pilot's interface to the flight management computer and functions for airplane startup, performance management, navigation and guidance, communications, and data display. The MFK contains multifunction switches that are really multilegend switches; with recent advances in flat panel display technology, the MFK has become a more practical reality.

The Boeing Crew Systems Research Group has proposed to the Air Force Flight Dynamics Laboratory a flat panel configuration consisting of programmable legend switches and a microprocessor and timing module. This particular MFK has 15 LED matrix readout devices that are single color, dot addressable, and capable of displaying a maximum of two rows of eight characters in a 5 by 7 ASCII font. A 7.6- by 11.4-cm (3- by 4.5-in) verification readout device is located just above the MFK. The display panel could be any of the solid-state technology (EL, LC, LED, or plasma) devices described earlier, because only alphanumeric messages and discrete readouts are required.

Use of the MFK for activation of individual switching functions does not itself reduce pilot workload. Workload reduction is achieved through the concept of sequential switching and programmed functions, which occur automatically based on stored inputs and control conditions. Sequenced switching is defined as a series of switching functions to be performed in sequence through pilot initiation of the sequence, all accomplished through a host computer.

A.4.5 VOICE-ACTUATED CONTROLS

By 1990, voice-actuated controls will become a reality for use in cockpits as an alternate, or possibly primary, means of communicating with the flight management computer system. Boeing is currently demonstrating such a system in the BCAC Crew Systems Research cab. In future applications, the computer will recognize a vocabulary of words spoken by the pilot and through software transfer the spoken commands into control and/or display actions.

REFERENCES

A-1 Leddy, W. J., and J. P. Heaton. Interim Report on Study of Asynchronous Multiple Sampling System. D6-49742, Boeing Commercial Airplane Company, March 12, 1981.

A-2 Small, V. J. Study of Asynchronous Multiple Sampling Systems. D6-51058TN, Boeing Commercial Airplane Company, 1981.

A-3 Small, V. J., and D. M. Hoover. Report on Protocol Research for Digital Data Buses To Be Used on Commercial Aircraft. D6-49728TN, Boeing Commercial Airplane Company, March 12, 1981.

A-4 Herzog, H. K. A Digital Terminal Access Communication System. D6-48847TN, Boeing Commercial Airplane Company, February 1980.

A-5 Wood, F. P., and H. K. Herzog. Experimental Data Bus—Current Mode Operation. D6-48774, Boeing Commercial Airplane Company, October 1979.

A-6 Smyth, R. K., ed., State of the Art Survey of Technologies Applicable to NASA's Aeronautics, Avionics and Controls Program. NASA CR-159050, Washington, D.C., May 1979.

A-7 Wise, K. D., K. Chen, and R. E. Yokely. Microcomputers: A Technology Forecast and Assessment to the Year 2000. John Wiley & Sons, New York, 1980.

A-8 Rang, E. R. Review of Digital Systems for Flight Controls. 80-SRC-99, Honeywell Systems and Research Center, Minneapolis, Minnesota, December 1980.

A-9 Lepselter, M. P. "A-Ray Lithography Breaks the Submicrometer Barrier." IEEE Spectrum, vol. 18, No. 5, May 1981, pp. 26-29.

A-10 Eklund, M. H., and W. L. Strauss, eds. Status '80, A Report on the Integrated Circuit Industry. Pitcher Technical Publications, Scottsdale, 1980.

A-11 Klass, P. J. "New Transistor Speed Exceeds Earlier Devices." Aviation Week and Space Technology, vol. 114, No. 13, March 30, 1981, p. 79.

A-12 Connolly, R. "VHSIC Finally Gets Untracked." Electronics, vol. 53, No. 1, January 3, 1980, pp. 81-85.

A-13 "Filter Center." Aviation Week and Space Technology, vol. 114, No. 9, March 2, 1981, p. 61.

A-14 Bursky, S. D. "Microprocessor—4- to 32-bit Pushback Performance Limits." Electronic Design, vol. 28, No. 24, November 22, 1980, p. 113.

A-15 Electronic Design. vol. 27, No. 24, November 22, 1979, pp. 51-52.

A-16 Electronic Design. vol. 29, No. 24, November 26, 1981, pp. 114-119.

A-17 Vail, P. J. "VLSI Memories, Problems, and Promise From a Military Viewpoint." ITC/USA/178. Proceedings of the International Telemetering Conference, Los Angeles, California, November 14-16, 1978 and Instrument Society of America, Pittsburgh, Pennsylvania, pp. 973-980.

A-18 Airplane Actuation Trade Study, Phase II—Design of Two Airplanes. D180-25487-2, Boeing Military Airplane Company, December 1980.

A-19 Pluhar, K. "Microelectronics Spur Changes Motor Selection." Control Engineering, vol. 27, No. 6, June 1980, pp. 58-61.

A-20 Electronic Flight Instruments (EFI). ARINC Characteristic 725, Annapolis, Maryland, November 16, 1979.

A-21 Teichner, W. H. "Color and Information Coding." Proceedings of the SID, vol. 20, No. 1, 1979, p. 3.

A-22 McCormick, E. J. Human Factors Engineering. McGraw Hill, New York, 1970, p. 106.

A-23 Kinney, J. S. "The Use of Color in Wide-Angle Display." Proceedings of the SID, vol. 20, No. 1, 1979, p. 33.

A-24 Krebs, M. J., and J. D. Wolf. "Design Principles for the Use of Color in Displays." Proceedings of the SID, vol. 20, No. 1, 1979, p. 12.

A-25 Seats, P. "CRT Improvements Planned and Ongoing." Proceedings of the SID, vol. 19, No. 4, 1978, p. 191.

A-26 Snyder, Harry L., PhD. Human Visual Performance and Flat Panel Display Image Quality. HFL-80-1/ONR-80-1, Office of Naval Research, July 1980.

A-27 Tannas, L. E., Jr., and W. F. Goede. "Flat Panel Displays: A Critique." IEEE Spectrum, vol. 15, No. 7, July 1978, pp. 26-32.

A-28 Ernstoff, M. N. "A Head-Up Display for the Future." Proceedings of the SID, vol. 19, No. 4, 1978, pp. 169-179.

A-29 Yoshida, M., K. Tanake, K. Taniguchi, T. Yamashita, Y. Kakihara, and T. Inoguchi. "AC Thin-Film EL Device That Emits White Light." Technical Digest, SID Symposium, April 1980, p. 107.

A-30 Raynes, E. P. "Liquid Crystal Display Devices." Proceedings on Electric Airborne Displays, AGARD-CP-167, April 11, 1975.

A-31 Shanks, I. A. "Multicolor Displays Using a Liquid Crystal Colour Switch." Proceedings on Electric Airborne Displays, AGARD-CP-167, April 11, 1975.

A-32 Sherr, S. Electronic Displays. Wiley, New York, 1979, pp. 113-135.

A-33 Luo, F. D., W. A. Hester, and T. P. Brody. "Alphanumeric and Video Performance of a 6 Inch by 6 Inch 30 Lines Per Inch Thin-Film Transistor Liquid Crystal Display Panel." Proceedings of the SID, vol. 19, No. 2, 1978, pp. 63-37.

APPENDIX B: FUNCTION CRITICALITY ASSESSMENT

This appendix includes function criticality assessments for top-level system functions, as shown in Table B-1.

Table B-1. Function Criticality Assessment (Page 1 of 16)

Function	Change pitch attitude via column deflection
Brief description	**Consequence of failure**
• Employs elevators to change or hold airplane pitch attitude	• Failure of function in flight would mean loss of control in the longitudinal axis and consequently loss of the airplane.
Flight criticality	Crucial (A), $< 10^{-9}$
Dispatch criticality	Yes
Remarks:	• Airplane must be designed to be safely landed with failure conditions specified in FAR 25.671 and 672.

Function	Adjust pitch attitude trim
Brief description	**Consequence of failure**
• Employs horizontal stabilizers to trim pitch attitude	• Degraded airplane handling quality • Flight envelope restrictions required for continuing accident-free flight and landing • Increased flightcrew workload
Flight criticality	Critical (B), $< 10^{-5}$
Dispatch criticality	Yes, 10^{-5} to 10^{-6}
Remarks:	• 10^{-5} to 10^{-6} is based on past demonstrated dispatch reliability. • Uncontrollable runaway must be shown to be extremely improbable.

Table B-1. Function Criticality Assessment (Continued) (Page 2 of 16)

Function	Change roll attitude via wheel deflection		
Brief description		**Consequence of failure**	
• Employs aileron and spoilers for roll control		• Airplane will be lost if function is lost in flight (no pilot action can avert).	
Flight criticality	Crucial (A), $<10^{-9}$	Remarks: • Airplane must be designed to be safely landed with failure conditions specified in FAR 25.671 and 672.	
Dispatch criticality	Yes		

Function	Adjust roll attitude trim		
Brief description		**Consequence of failure**	
• Relieves input feel forces by relocating the neutral position of the feel and centering mechanism		• Degraded airplane handling quality • Increased flightcrew workload • No specific restrictions apply but added caution should be exercised by pilot.	
Flight criticality	Workload relief (D), 10^{-3}	Remarks: • May be dispatched if one channel of autopilot is working	
Dispatch criticality	Yes, 10^{-5} to 10^{-6}		

Table B-1. Function Criticality Assessment (Continued) (Page 3 of 16)

Function	Change airplane direction or side-slip angle via rudder deflection
Brief description	**Consequence of failure**
• Employs rudder to attain directional control for the airplane	• Landing at nearest suitable airport is required. • Hazardous increase in flightcrew workload occurs. • On landing, directional control could be maintained with the brakes, asymmetric reverse thrust, or at low speeds with nose steering. Notes: • Normally, airplane can be marginally controlled in yaw by using ailerons and spoilers (resulting in degraded airplane handling quality), except following an inadvertent engine cut. • The function would become crucial if the ailerons and spoilers are not working and/or there is an inadvertent engine cut. However, the probability of occurrence for either event is quite remote; therefore, it is defined as a critical function.

Flight criticality	Critical (B), $<10^{-7}$	Remarks: • Rudder must be designed to meet flight control failure conditions as specified in FAR 25.671 and 672 for safe landing.
Dispatch criticality		

Function	Modify pitch control characteristic—elevator feel
Brief description	**Consequence of failure**
• Provides elevator normal control wheel feel through all flight regimes (includes Mach No., speed, trim, and pitch augmentation)	• Fly the airplane normally and avoid abrupt elevator inputs. • Added care and caution required because pilot authority is not limited and the pilot could exceed V/g envelope at high speeds.

Flight criticality	Critical (B), 10^{-3} to 10^{-4}	Remarks: • 10^{-5} to 10^{-6} is based on past demonstrated dispatch reliability
Dispatch criticality	Yes, 10^{-5} to 10^{-6}	

Function	Modify pilot's roll control authority
Brief description	**Consequence of failure**
• Provides increased roll control at lower airspeeds and safeguard from high-speed reversal and from excessive roll control forces by locking out outer ailerons from direct pilot control as flaps are retracted	• Pilot should fly the airplane with caution at high speeds (possible envelope limiting).
Flight criticality	Critical (B), 10^{-3} to 10^{-4}
Dispatch criticality	Yes, 10^{-5} to 10^{-6}
Remarks:	

Function	Modify yaw control characteristic
Brief description	**Consequence of failure**
• Reduces input signal to move rudder as a function of airspeed (ratio changer, load limiter, etc.)	• Airplane can be flown normally with caution and certain (envelope) restrictions such as— • Avoiding abrupt rudder inputs at high speed (with flaps up) • Reduction of crosswind capability (with flaps down)
Flight criticality	Critical (B), 10^{-3} to 10^{-4}
Dispatch criticality	Yes, 10^{-5} to 10^{-6}
Remarks:	

Table B-1. Function Criticality Assessment (Continued) (Page 5 of 16)

Function	Augment short-period mode pitch axis stability
Brief description	**Consequence of failure**
• Augments airplane longitudinal stability to provide safe and acceptable handling qualities throughout flight envelope	• The airplane will be lost and no pilot action can avert a catastrophic accident.

Flight criticality	Crucial (A), $<10^{-9}$	Remarks: • The preceding statements apply only to a longitudinally unstable airplane with time-to-double amplitude short enough to indicate manual stabilization is not achievable.
Dispatch criticality	Yes	

Function	Augment speed mode pitch axis stability
Brief description	**Consequence of failure**
• Augments airplane longitudinal stability to provide desired handling quality	• Unable to consistently stabilize airplane with changing airspeed • Flight handling qualities may be improved by reducing airplane speed (e.g., envelope restriction) • May result in some safety hazard but it can be averted by proper pilot action or flight envelope change

Flight criticality	Critical (B), 10^{-3} to 10^{-4}	Remarks:
Dispatch criticality	Yes	

Table B-1. Function Criticality Assessment (Continued) (Page 6 of 16)

Function	Augment roll-yaw axis stability (LAS)
Brief description	**Consequence of failure**
• Provides good handling qualities by preventing Dutch roll (similar to conventional yaw damper in criticality)	• Unable to adequately damp Dutch-roll mode in cruise • Degraded airplane handling qualities • Complete loss of LAS in critical flight condition could result in loss of the airplane, but such loss can be averted by proper crew action to restrict the airplane flight envelope. • Cannot be dispatched on ground because LAS is required for limiting structural loads

Flight criticality	Critical (B), 10^{-3} to 10^{-4}	Remarks:
Dispatch criticality	Yes	

Function	Limit angle of attack (AAL)
Brief description	**Consequence of failure**
• Prevents the airplane from entering a locked-in stall position (assumes locked-in stall is characteristic of an ACT airplane)	• Unable to provide warning and/or positive angle-of-attack limiting when airplane approaches a stall; hence, airplane could stall and be lost • Special caution must be exercised but no specific restrictions apply • Cannot be dispatched on ground because of loss of safety margin

Flight criticality	Critical (B), $<10^{-4}$	Remarks: • AAL becomes a crucial function in locked-in conditions. However, the probability of the pilot stalling the airplane is $< 10^{-7}$. Hence, AAL is defined as a critical function for operation because loss of AAL and airplane entering deep stall simultaneously are extremely improbable.
Dispatch criticality	Yes	

Table B-1. Function Criticality Assessment (Continued) (Page 7 of 16)

Function	Gust-load alleviation (GLA)	
Brief description	**Consequence of failure**	
• Reduces the wing structure loading resulting from gust penetration	• Unable to control gust-load onset through deflections of wing controls and to pitch the airplane into the gust through commands to the elevators • Unable to reduce structural loading at low, rigid-body frequencies • Allows continuation of normal flight schedule after GLA is lost in the air because the airplane structure ultimate strength exceeds the design limit load • Cannot be dispatched on ground because the airplane structural strength is less than the design ultimate load at maximum gross weight	
Flight criticality	Critical (B), 10^{-3} to 10^{-4}	Remarks:
Dispatch criticality	Yes	

Function	Maneuver-load control	
Brief description	**Consequence of failure**	
• Reduces wing vertical bending moments during maneuvering in flight	• Unable to modulate outboard and/or inboard control surfaces to reshape the wing-span load distribution • Allows continuation of normal flight schedule after MLC is lost in the air because the airplane structure ultimate strength exceeds the design limit load • Cannot be dispatched on ground because the airplane structural strength is less than the design ultimate load	
Flight criticality	Critical (B), 10^{-3} to 10^{-4}	Remarks:
Dispatch criticality	Yes	

Function	Flutter-mode control	
Brief description	**Consequence of failure**	
• Increases modal damping at the flutter frequency (provides required flutter stability at speeds above V_D)	• Unable to increase the airplane flutter placard speed by actively suppressing (increasing the damping of) selected flutter modes • Flutter can occur if V_D is exceeded; therefore, pilot should reduce speed to reduce likelihood of occurrence. • Can be dispatched with flight envelope restrictions • Low damped oscillations of critical flutter modes may occur above V_D.	
Flight criticality	Critical (B), 10^{-3} to 10^{-4}	Remarks: • FMC becomes crucial for airspeeds above V_D/M_D. Because loss of FMC and speed $>V_D/M_D$ simultaneously are extremely improbable ($<10^{-9}$), FMC is defined as a critical function.
Dispatch criticality	No	

Function	Display airspeed and Mach No.	
Brief description	**Consequence of failure**	
• Provides pilot with required airspeed and Mach data for airplane in manual flight mode	• Flight envelope restriction and airplane altitude limited to maximum of (TBD)m (ft) • Hazardous increase in flightcrew workload especially during landing mode • Possibility of stalling the airplane • Safe landing dependent on weather condition (visibility), avoiding a stall, proper ATC guidance, and other autoland system (see Remarks).	
Flight criticality	Critical (B), 10^{-4}	Remarks: Standby instrument pneumatic airspeed indicator is adequate for pilot's prevention of stall.
Dispatch criticality	Yes	

Table B-1. Function Criticality Assessment (Continued) (Page 9 of 16)

Function	Display altitude	
Brief description	**Consequence of failure**	
• Provides pilot with required attitude data for airplane in manual flight mode	• Hazardous increase in flightcrew workload especially during landing mode • Flight envelope and/or mission restriction required	
Flight criticality	Critical (B), $<10^{-5}$	Remarks: Standby pneumatic altimeter provides safe "get home" data to pilot.
Dispatch criticality	Yes	

Function	Display vertical speed	
Brief description	**Consequence of failure**	
• Provides pilot with required vertical speed data for airplane in manual flight mode	• Flightcrew workload is increased significantly especially during takeoff and approach landing. • Pilot must use other means (time consuming and slow) to obtain vertical speed.	
Flight criticality	Critical (B), $<10^{-4}$	Remarks:
Dispatch criticality		

Table B-1. Function Criticality Assessment (Continued) (Page 10 of 16)

Function	Display attitude, pitch, and roll	
Brief description	**Consequence of failure**	
• Provides pilot with attitude information for airplane in manual flight mode	• Hazardous increase in flightcrew workload especially during landing • Flight envelope restriction required	
Flight criticality	Critical (B), $<10^{-5}$	Remarks: Standby attitude indicator provides adequate "get home" attitude indication to pilot.
Dispatch criticality	Yes	

Function	Display engine thrust	
Brief description	**Consequence of failure**	
• Provides pilot with engine thrust and thrust limit data for manual takeoff, climb, cruise, descent, and landing modes	• May affect precision or economy of flight • May slightly increase flightcrew workload (pilot may have to exercise caution)	
Flight criticality	Workload relief (D), 10^{-3}	Remarks:
Dispatch criticality	Yes	

Table B-1. Function Criticality Assessment (Continued) (Page 11 of 16)

Function	Display direction (heading and track)	
Brief description	**Consequence of failure**	
• Provides pilot with required heading and track data for airplane in manual flight mode	• Substantial increase in flightcrew workload to derive means of reaching an airport and runway for safe landing • Flight and mission envelope restrictions • Emergency procedures and/or immediate landing may be necessary	
Flight criticality	Critical (B), $<10^{-5}$	Remarks: Standby compass provides adequate directional information to pilot for continued flight and landing.
Dispatch criticality	Yes	

Function	Display bearing and/or distance to navigation aids	
Brief description	**Consequence of failure**	
• Includes ADF, VOR navigation system, and DME	• Unable to provide relative bearing and distance of ground stations with respect to airplane heading • Increases flightcrew workload • Flight envelope and/or mission restrictions likely	
Flight criticality	Critical (B), 10^{-3} to 10^{-4}	Remarks: Alternative navigation systems will probably be available in 1990s environment.
Dispatch criticality	Yes	

Table B-1. Function Criticality Assessment (Continued) (Page 12 of 16)

Function	Display deviation from selected landing system path		
Brief description		**Consequence of failure**	
• Provides pilot with glide slope and localizer data required for manual landing mode		• Unable to provide information showing deviation from the established glide slope and runway centerline • Increases flightcrew workload • Possibility of diversion to another airport for safe landing because of poor visibility (weather) condition	
Flight criticality	Critical (B), 10^{-3} to 10^{-4}	Remarks:	
Dispatch criticality	Yes		

Function	Communications with voice		
Brief description		**Consequence of failure**	
• Includes HF and VHF communications (air to ground and ground to air)		• The flight will be restricted to VFR (VMC) meteorological conditions.	
Flight criticality	Critical (B), 10^{-3} to 10^{-4}	Remarks:	
Dispatch criticality	Yes		

Table B-1. Function Criticality Assessment (Continued) (Page 13 of 16)

Function	Airplane identification via transponder	
Brief description	**Consequence of failure**	
• Transmits airplane ID code to ATC system	• Unable to identify airplane without other source of communications	
Flight criticality	Workload relief (D), 10^{-3}	Remarks:
Dispatch criticality	Yes	

Function	Pilot-assisted steering	
Brief description	**Consequence of failure**	
• Attitude hold autopilot, which allows pilot to change attitude references (heading)	• Increases pilot workload marginally • Might affect precision or economy of flight	
Flight criticality	Workload relief (D), 10^{-3}	Remarks:
Dispatch criticality		

Table B-1. Function Criticality Assessment (Continued) (Page 14 of 16)

Function	Capture and maintain flight parameters for automatic flight	
Brief description	**Consequence of failure**	
• Comprises thrust, speed, Mach No., heading, and track	• Increases pilot workload • Might affect precision or economy of flight	
Flight criticality	Workload relief (D), 10^{-3}	Remarks:
Dispatch criticality		

Function	Capture and track landing system path	
Brief description	**Consequence of failure**	
• Landing systems such as ILS and MLS	• Diversion is highly probable if visibility is marginal for safe landing (mission restriction). • Flightcrew workload is increased significantly.	
Flight criticality	Critical (B), $<10^{-4}$	Remarks: With loss of function in Category III weather conditions, below a certain altitude, neither safe landing nor safe go-around is possible, so probability of occurrence below decision height must be shown to be extremely improbable.
Dispatch criticality	Yes	

Table B-1. Function Criticality Assessment (Continued) (Page 15 of 16)

<table>
<tr><td>Function</td><td colspan="3">Use autonavigation and guidance</td></tr>
<tr><td colspan="2">Brief description</td><td colspan="2">Consequence of failure</td></tr>
<tr><td colspan="2">• Determines airplane state (position and velocity)
• Provides flight parameter targets to follow optimal flight profile</td><td colspan="2">• Unable to provide necessary information to achieve economy and precision of flight
• May possibly increase flightcrew workload</td></tr>
<tr><td>Flight criticality</td><td colspan="2">Workload relief (D), 10^{-3}</td><td rowspan="2">Remarks:</td></tr>
<tr><td>Dispatch criticality</td><td colspan="2"></td></tr>
</table>

<table>
<tr><td>Function</td><td colspan="3">Monitor information displays</td></tr>
<tr><td colspan="2">Brief description</td><td colspan="2">Consequence of failure</td></tr>
<tr><td colspan="2">• Displays selected thrust limits
• Displays desired flight profile
• Displays airplane state (position and velocity)
• Displays performance handbook data (including ACT failure envelope)
• Displays autoflight pitch, roll, airspeed, and thrust commands</td><td colspan="2">• Unable to provide needed information in a relatively short period of time
• Will probably affect economy and/or precision of flight
• Increases flightcrew workload slightly</td></tr>
<tr><td>Flight criticality</td><td colspan="2">Workload relief (D), 10^{-3}</td><td rowspan="2">Remarks:
Essential flight parameters are provided by standby instruments.</td></tr>
<tr><td>Dispatch criticality</td><td colspan="2"></td></tr>
</table>

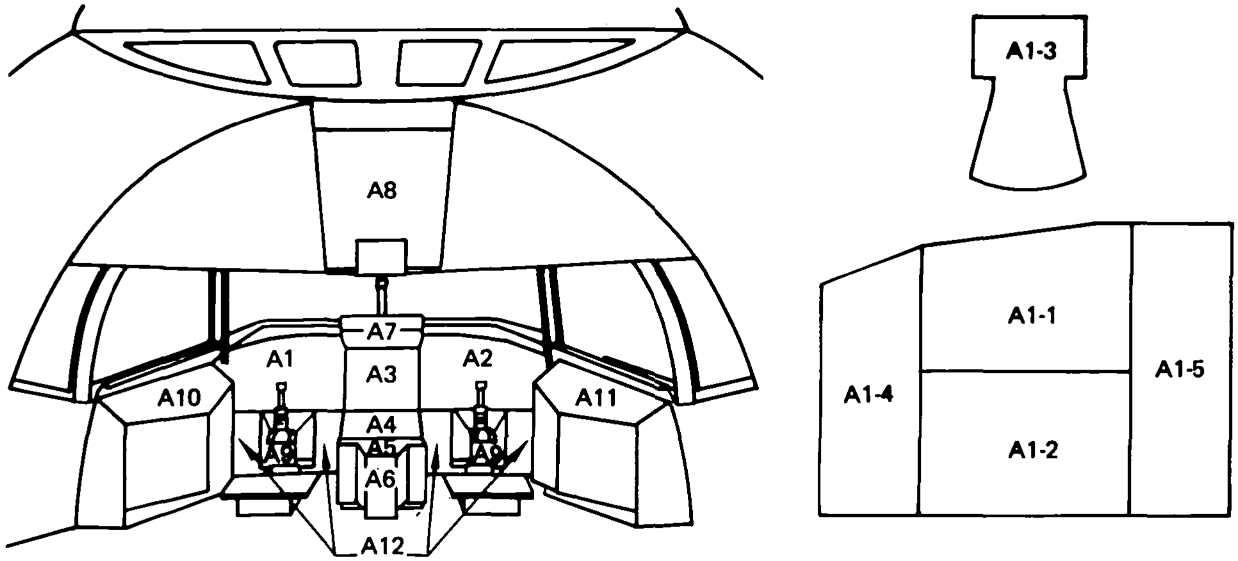
<table>
<tr><td>Function</td><td colspan="2">ACT system flight condition alerts</td></tr>
<tr><td colspan="2">Brief description</td><td>Consequence of failure</td></tr>
<tr><td colspan="2">• Provides pilot with visual and/or aural warnings of critical ACT system failures</td><td>• Unable to provide indication (warning) when one or more of the ACT functions fail
• Unable to inform flightcrew of proper flight envelope and/or mission restriction(s) to avert an accident
• Will increase flightcrew workload significantly</td></tr>
<tr><td>Flight criticality</td><td>Critical (B), 10^{-4} to 10^{-9}, situation dependent</td><td rowspan="2">Remarks:
• The level of redundancy required is not considered or addressed here.
• A disastrous accident in this case is contingent upon failure of—
• A critical ACT function
• The associated alerting system to notify pilot
• The pilot detecting the event from changed handling qualities and performing needed action to avert a probable accident</td></tr>
<tr><td>Dispatch criticality</td><td></td></tr>
</table>

<table>
<tr><td>Function</td><td colspan="2">Flight control system status alerts</td></tr>
<tr><td colspan="2">Brief description</td><td>Consequence of failure</td></tr>
<tr><td colspan="2">• Provides pilot with visual and/or aural warnings of critical flight control system failures</td><td>• Unable to inform pilot automatically when one or more of the flight control systems fails and subsequently to have the appropriate actions taken (such as flight and/or mission restriction, emergency procedures, etc.) to avert an accident</td></tr>
<tr><td>Flight criticality</td><td>Critical (B), 10^{-4} to 10^{-9}, situation dependent</td><td rowspan="2">Remarks:
• The minimum level of redundancy for a safe flight is not considered or addressed here.
• A disastrous accident in this case is contingent upon failure of—
• A critical flight control system
• The associated alerting system to warn pilot
• The pilot detecting the event from changed handling qualities and performing needed action to avert a probable accident</td></tr>
<tr><td>Dispatch criticality</td><td>Yes</td></tr>
</table>

APPENDIX C: FLIGHT DECK SYSTEM TOTAL CONTROL AND DISPLAY FUNCTIONAL FEATURES

APPENDIX C: FLIGHT DECK SYSTEM TOTAL CONTROL AND DISPLAY FUNCTIONAL FEATURES LIST

This appendix defines the flight deck control and display system total functions list for a 1990s Active Controls Technology (ACT) airplane with all-electronic flight deck. "Typical" functional locations of the controls and displays are also depicted in Figures C-1 through C-10. This cockpit configuration is similar to that developed previously (ref C-1). The flight deck compartment is divided into twelve major surface areas, each of which accommodates the control or display system elements (designated by dash numbers) and the functions associated with those elements.



A1-1 EADI

Display functions:

- Reference airplane
- Roll-angle pointer and scale
- Pitch attitude
- Pitch reference line
- Artificial horizon
- Airspeed
- Mach
- Airspeed references
- Speed error
- Barometric altitude setting
- Barometric altitude
- Radio altitude
- Vertical speed
- Sky/ground color shading
- ILS/MLS glide slope
- ILS/MLS localizer
- ILS box
- Pitch and roll flight director command
- Flightpath acceleration
- Commanded flightpath acceleration
- Flightpath angle
- Commanded flightpath angle
- Drift angle
- Windshear
- Perspective runway
- Extended runway centerline
- Low-light-level television
- Rate of turn
- Angle of attack
- Angle-of-attack control
- Excessive deviation indication
- Thrust command
- Decision height indication
- Indication of V_1, V_2, and V_{REF}
- Altitude alert
- Ground proximity
- Approach progress annunciation
  - LOC capture
  - G/S capture
  - Autoland
  - Flare
  - Rollout
  - Turnoff
  - Go-around

Control functions:

- Takeoff
- Climb
- Cruise
- Descent
- Land
- Taxi
- Pitch reference knob
- Decision height knob
- Submodes
  - Speed error
  - Flight director
  - Approach television
  - ILS/MLS
  - Runway
  - Windshear
  - Pitch reference
  - Angle of attack
- Brightness control
- Test

Figure C-1. Captain's Main Panel (A1)

A1-2 EHSI

Display functions:

- Airplane symbol
- Compass rose
- Present track
- Present heading
- Present course
- Magnetic and true annunciation
- Course select
- Track select
- Heading select
- Straight-trend vector
- Curved-trend vector
- Flight plan paths
- Time navigation
- Terminal area routes
- Altitude and range predictions
- Altitude and speed predictions
- Navigation aids
- Airports
- Terrain and obstacles
- Geographic reference points
- Waypoint identification
- Waypoint altitude
- Waypoint ground speed
- Distance-to-go
- Time-to-go
- Bearing to waypoint
- Ground speed
- Cockpit display of traffic information (CDTI)
- Wind speed
- Wind direction
- Back course identification
- Map scale
- Weather radar
- Horizontal deviation
- Vertical deviation
- Runway
- Extend runway centerline
- Marker beacon
  - —Outer
  - —Middle
  - —Inner
- Performance management error
- Flight mode annunciation

Control functions:

- Course select
- Heading select
- Track select
- North-up map
- Track-up map
- Altitude and range select
- Speed and range select
- Horizontal and vertical deviation
- CDTI
- Navigation aids
- Terrain
- Airports
- Waypoints
- Geographic reference points
- Trend vector
- Time navigation
- Fuel navigation
- Test
- Map scale
- Navigation sources
  - —VOR
  - —ILS/MLS
  - —IRS
  - —FMC
  - —Data link
  - —Omega
  - —GPS
- Weather radar
- Map
- Flight plan

A1-3 HEAD-UP DISPLAY (HUD)

Display functions:

- Reference airplane
- Roll-angle pointer and scale
- Pitch attitude
- Pitch reference line
- Artificial horizon
- Airspeed
- Mach
- Speed error
- Barometric altitude
- Radio altitude
- Pitch and roll flight director command
- Flightpath acceleration
- Commanded flightpath acceleration
- Flightpath angle
- Commanded flightpath angle
- Heading
- Track-angle pointer and scale
- Drift angle
- Perspective runway
- DME
- ILS box
- Decision height
- Master warning and caution

Control functions:

- Takeoff
- Climb
- Cruise
- Descent
- Land
- Pitch reference knob
- Decision height knob
- Brightness control
- Test
- Declutter

Figure C-1. Captain's Main Panel (A1) (Continued)

A1-4 CONTROLS AND INDICATORS

Display functions:
- Backup airspeed and Mach
  - –Airspeed
  - –Mach
  - –Airspeed references
- Backup RMI
  - –VOR/ADF 1
  - –VOR/ADF 2
  - –To-from station identification
  - –DME 1
  - –DME 2

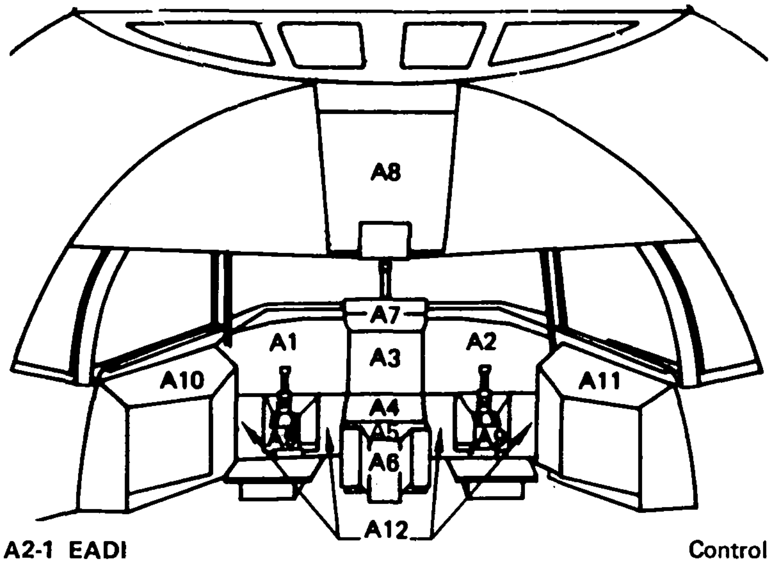
Control functions:
- Airspeed references select
- VOR/ADF selections
- EADI/HUD control panel
- EHSI control panel

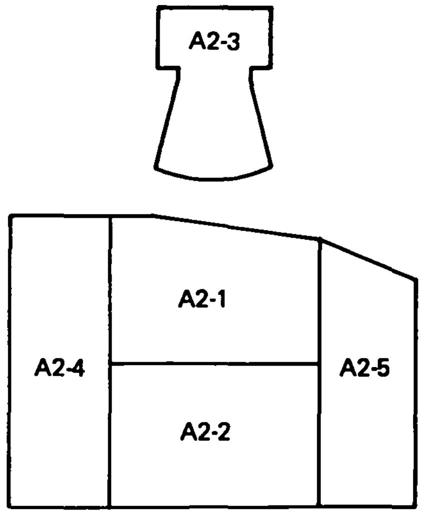
A1-5 CONTROLS AND INDICATORS

Display functions:
- Radio and barometric altitude
  - –Barometric altitude setting
  - –Barometric altitude
  - –Radio altitude
- Vertical speed
- Clock
- Warning/caution/advisory
  - –Central readout of warning/caution condition
  - –Automatic intensity control of aural and visual
  - –Limited number of aural sounds
  - –Three levels of urgency
  - –Interface with ACT maintenance display

Control functions:
- Barometric altitude setting select
- Clock start
- Clock stop
- Time set
- Warning/caution/advisory message cancel
- Warning/caution/advisory message recall

Figure C-1. Captain's Main Panel (A1) (Concluded)





A2-1 EADI

Control and display functions:
(same as A1-1 EADI)

A2-2 EHSI

Control and display functions:
(same as A1-2 EHSI)

A2-3 HUD

Control and display functions:
(same as A1-3 HUD)

A2-4 CONTROLS AND INDICATORS

Display functions:

- Backup airspeed and Mach
- Backup RMI
- Clock
- Warning/caution/advisory
- Backup true airspeed
- Backup ground speed
- Static air temperature

Control functions:

- Airspeed reference select
- VOR/ADF selections
- Clock start
- Clock stop
- Time set
- Warning/caution/advisory message cancel
- Warning/caution/advisory message recall

A2-5 CONTROLS AND INDICATORS

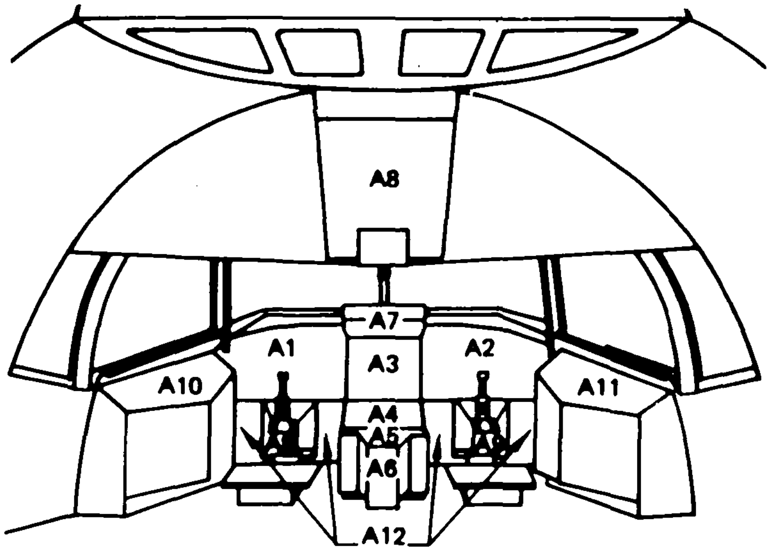
Display functions:

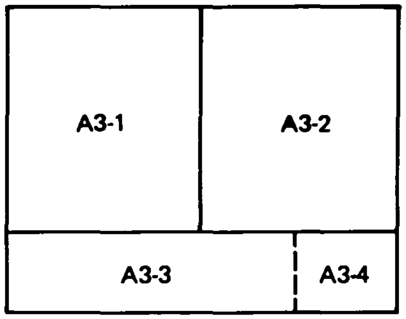
- Radio and barometric altitude
- Vertical speed

Control functions:

- Barometric altitude setting select
- EADI/HUD control panel
- EHSI control panel

Figure C-2. First Officer's Main Panel (A2)





A3-1 DISPLAYS AND CONTROLS

Display functions:

- Engine 1 pressure ratio
- Engine 2 pressure ratio
  - —Actual EPR
  - —Commanded EPR
  - —EPR limit
  - —Takeoff EPR
- Engine 1 N1
- Engine 2 N1
- Engine 1 EGT
- Engine 2 EGT
- Engine 1 N2
- Engine 2 N2
- Engine 1 fuel flow
- Engine 2 fuel flow
- Engine 1 oil pressure
- Engine 2 oil pressure
- Engine 1 oil temperature
- Engine 2 oil temperature
- Engine 1 oil quantity
- Engine 2 oil quantity
- Engine 1 vibration—turbine
- Engine 2 vibration—turbine
- Engine 1 vibration—inlet
- Engine 2 vibration—inlet
- Engine 1 oil filter bypass
- Engine 2 oil filter bypass
- Engine 1 reverser unlocked
- Engine 2 reverser unlocked
- Engine 1 low oil pressure
- Engine 2 low oil pressure
- Thrust reverser hydraulic accumulator low pressure
- Flight profiles
- Weight limitations
  - —Maximum taxi
  - —Maximum takeoff
  - —Maximum landing
  - —Maximum zero fuel
- Takeoff and landing
  - —Temperature
  - —Altitude
  - —Runway slope
  - —Tailwind
  - —Crosswind
- Maximum operating altitudes
- Brake energy and temperature
- Airspeed
  - —Turbulent air
  - —Emergency descent
  - —Landing gear operating
  - —Landing gear extended
  - —Landing gear maximum retract
  - —Tire placard
  - —Flaps
  - —Minimum control speed
- Powerplant limitations
  - —EPR
  - —RPM
  - —EGT
  - —Starting cycle
  - —Duct pressure
  - —Ignition system
  - —Icing conditions
  - —Engine oil systems
  - —Engine fuel systems
- Pneumatic system limitations
- Electrical power system limitations

Figure C-3. Pilot's Center Panel (A3)

- Fuel system limitations
- Ice and rain protection system limitations
- Air-conditioning and pressurization system limitations
- Hydraulic power system limitations
- Landing gear system limitations
- Flight control system limitations
- Navigation equipment limitations
- Automatic flight system limitations
- Center-of-gravity limitations
- Communication equipment limitations
- Warning systems limitations
- Fire protection system limitations
- Oxygen system limitations
- Lighting system limitations
- Emergency equipment limitations
- Auxiliary power unit limitations
- Water and waste limitations
- Servicing limitations

Control functions:
- Basic select
- Engine systems select
- Flight profiles select
- Operating limits select
- Brightness control
- Test
- Editing

A3-2 DISPLAYS AND CONTROLS

Display functions:
- Fuel
  —Tank 1 fuel quantity
  —Tank 2 fuel quantity
  —Center tank fuel quantity
  —Total fuel quantity
  —Tank 1 fuel temperature
  —Aft pump 1 low pressure
  —Forward pump 1 low pressure
  —Aft pump 2 low pressure
  —Forward pump 2 low pressure
  —Center R pump low pressure
  —Engine 1 fuel filter icing
  —Engine 2 fuel filter icing
  —Fuel and cg management
- Electrical
  —dc amperes—standby power
  —dc amperes—No. 2 standby power
  —dc amperes—battery bus
  —dc amperes—battery
  —dc amperes—TR1
  —dc amperes—TR2
  —dc amperes—TR3
  —dc volts—standby power
  —dc volts—No. 2 standby power
  —dc volts—battery bus
  —dc volts—battery
  —dc volts—TR1
  —dc volts—TR2
  —dc volts—TR3
  —ac volts—standby power
  —ac volts—No. 2 standby power
  —ac volts—ground power
  —ac volts—generator 1
  —ac volts—generator 2
  —ac volts—APU generator
  —Frequency—standby power
  —Frequency—No. 2 standby power
  —Frequency—ground power
  —Frequency—generator 1
  —Frequency—generator 2
  —Frequency—APU generator
  —CSD 1 drive oil temperature in
  —CSD 2 drive oil temperature in
  —CSD 1 drive oil temperature rise
  —CSD 2 drive oil temperature rise
  —Generator 1 ac amperes
  —Generator 2 ac amperes
  —APU generator ac amperes
  —CSD 1 drive low oil pressure
  —CSD 2 drive low oil pressure
  —CSD 1 drive high oil pressure
  —CSD 2 drive high oil pressure
  —Standby power off
  —No. 2 standby power off
  —ac standby bus off
  —Data output mode
  —Generator bus 1 off
  —Generator bus 2 off
  —Transfer bus 1 off
  —Transfer bus 2 off
  —Equipment cooling off
  —Transfer bus 1 on
  —Transfer bus 2 on
- Hydraulic power
  —System A pressure
  —System B pressure
  —System A quantity
  —System B quantity
  —Standby quantity
  —A pump 1 low pressure
  —A pump 2 low pressure
  —B pump 1 low pressure
  —B pump 2 low pressure
  —Standby low pressure
  —B pump 1 overheat
  —B pump 2 overheat
- Pneumatics, air-conditioning, and pressurization
  —Bleed air pressure—left duct
  —Bleed air pressure—right duct
  —Air temperature—supply duct
  —Air temperature—passenger cabin
  —Cabin altitude

Figure C-3. Pilot's Center Panel (A3) (Continued)

—Cabin rate of climb
—Cabin differential pressure
—Pressure altitude
—Pack trip off—left
—Pack trip off—right
—Wing-body overheat—left
—Wing-body overheat—right
—Bleed trip off—left
—Bleed trip off—right
—Auto fail
—Off schedule descent
—Duct overheat—left
—Duct overheat—right
—APU bleed valve open

- Flight controls
  —ACT disconnected
  —ACT preflight test status (electrical)
  —ACT preflight test status (mechanical)
  —ACT maintenance display
  - System faults
  - Function status
  - Advisory messages (dispatchability, flight restrictions)
  - Operations decisions

  —Mach trim failure
  —LAS off (replaces yaw damper)
  —Feel differential pressure
  —Flight control A low pressure
  —Flight control B low pressure
  —Autopilot stabilizer out of trim
  —Speedbrakes armed
  —Speedbrakes do not arm
  —Stabilizer trim rate
  —Stabilizer trim (automatic/manual)
  —Mach trim
  —Autotrim
  —Outboard aileron lockout
  —Spoiler feedback
  —LAS (replaces yaw damper)
  —Aileron feel
  —Elevator feel
  —Rudder ratio
  —Rudder feel
  —Dedicated "q" computation
  —LE flaps in transit
  —LE flaps extend
  —LE flap full extend
  —Left-flap position
  —Right-flap position
  —Rudder position
  —Elevator position
  —Aileron position
  —Stabilizer position
  —Slat 1 in transit
  —Slat 2 in transit
  —Slat 3 in transit
  —Slat 4 in transit
  —Slat 5 in transit
  —Slat 6 in transit
  —Flap 1 in transit
  —Flap 2 in transit
  —Flap 3 in transit
  —Flap 4 in transit
  —Slat 1 intermediate extend
  —Slat 2 intermediate extend
  —Slat 3 intermediate extend
  —Slat 4 intermediate extend
  —Slat 5 intermediate extend
  —Slat 6 intermediate extend
  —Slat 1 full extend
  —Slat 2 full extend
  —Slat 3 full extend
  —Slat 4 full extend
  —Slat 5 full extend
  —Slat 6 full extend
  —Flap 1 full extend
  —Flap 2 full extend
  —Flap 3 full extend
  —Flap 4 full extend
- Landing gear and brakes
  —Hydraulic brake pressure—system A
  —Hydraulic brake pressure—system B
  —Left landing gear warning
  —Nose landing gear warning
  —Right landing gear warning
  —Additional landing gear warnings (as required for ACT unconventional landing gear)
  —Ground sensing relay
  —Antiskid inoperative—inboard
  —Antiskid inoperative—outboard
  —Thrust lever 1—idle
  —Thrust lever 2—idle
  —Autobrake off
  —Autobrake maximum
  —Autobrake minimum
  —Gear up
  —Gear down
  —Landing gear armed
  —Landing gear does not arm
- Oxygen
  —Crew oxygen pressure
  —Passenger oxygen pressure
  —Crew oxygen quantity
  —Passenger oxygen quantity
- Ice and rain protection
  —Left-side window heat
  —Left-forward window heat
  —Right-side window heat
  —Right-forward window heat
  —Engine 1 anti-ice
  —Engine 2 anti-ice

Figure C-3. Pilot's Center Panel (A3) (Continued)

- –Pitot-static system A
- –Pitot-static system B
- –Stall warning heat
- –Left wing anti-ice
- –Right wing anti-ice

- Auxiliary power unit
  - –EGT
  - –Low oil pressure
  - –High oil pressure
  - –Overspeed
- Weight and balance
- Normal checklists
  - –Before start
  - –After start
  - –Taxi–before takeoff
  - –After takeoff
  - –Descent and approach
  - –Landing
  - –Ramp
- Emergency/abnormal checklist
  - –Powerplant
    - Engine fire, severe damage, or separation
      - –Primary
      - –Secondary
    - Engine overheat
    - Engine shutdown (in-flight)
    - Engine start (in-flight)
    - 1 engine-inoperative landing
      - –Descent and approach
      - –Landing
      - –Go-around
    - Reverser unlock or operating light on
    - Low oil pressure light on
    - Oil filter bypass light on
  - –Electrical
    - Electrical system smoke or fire
      - –Primary
      - –Secondary
    - CSD low-oil-pressure light on
    - CSD high-oil-temperature light on
    - Standby-power-off light on (No. 1)
    - Standby-power-off light on (No. 2)
    - Bus-off light(s) on
    - Transfer-bus-off light(s) on
    - Equipment-cooling-off light on
    - Circuit breaker trip
  - –Hydraulic, landing gear, and brakes
    - System A quantity to zero
      - –Descent and approach
      - –Landing
    - Hydraulic-pump low-pressure light on
    - Hydraulic B-pump-overheat light on
    - System B quantity to zero
      - –Descent and approach
      - –Landing
    - Landing gear lever will not move to UP after takeoff
    - Landing gear unsafe indication
    - Loss of both A and B hydraulic systems
      - –Descent and approach
      - –Landing
      - –After touchdown
    - Gear-not-sealed light on
    - Partial gear landing
    - One antiskid-inoperative light on
    - Both antiskid-inoperative lights on
    - Loss of A or B system hydraulic brake pressure
  - –Fuel
    - Fuel-heat valve inoperative
    - Filter-icing light on
    - Crossfeed selector inoperative
    - Low-pressure light on
    - Minimum fuel go-around
    - Fuel and cg management
  - –Pneumatic, air-conditioning, and pressurization
    - Rapid depressurization
      - –Primary
      - –Secondary
    - Emergency descent
      - –Primary
      - –Secondary
    - Duct-overheat light on
    - Pack-tripoff light on
    - Pack-overheat light on
    - Bleed-trip-off light on
    - Autofail light on
    - Off-schedule-descent light on
  - –Fire and smoke evaluation
    - Wheel well fire
    - APU fire
    - Control and passenger cabin smoke evacuation
      - –Cabin pressurized
      - –Cabin unpressurized
  - –Window heat and anti-ice
    - Control cabin window failure
    - Window-overheat light on
    - Window-heat-on light out
    - Engine anti-ice valve inoperative
    - Wing anti-ice valve inoperative
  - –Flight controls
    - Runaway stabilizer
    - Abnormal flight controls
    - Jammed stabilizer
      - –Descent and approach
      - –Landing

Figure C-3. Pilot's Center Panel (A3) (Continued)

- Flap asymmetry unsymmetrical or no LE devices
- Flight-control low-pressure light on
- Feel-differential-pressure light on
- LAS light on (replaces yaw damper)
- Stabilizer-out-of-trim light on
- Speedbrakes-do-not-arm light on
- Mach-trim-fail light on
- ACT disconnected
- ACT preflight test failure
- Autotrim failure
- ACT fault status advisory

—Abnormal landing

Control functions:

- Basic select
- Systems select
- Normal checklist select
- Emergency/abnormal checklist select
- Caution select
- Test select
- Brightness control
- Editing keys

A3-3 CONTROLS AND INDICATORS

- Left-flap position
- Right-flap position
- Rudder position
- Elevator position
- Aileron position
- Stabilizer position
- Slat 1 in transit
- Slat 2 in transit
- Slat 3 in transit
- Slat 4 in transit
- Slat 5 in transit
- Slat 6 in transit
- Flap 1 in transit
- Flap 2 in transit
- Flap 3 in transit
- Flap 4 in transit
- Slat 1 intermediate extend
- Slat 2 intermediate extend
- Slat 3 intermediate extend
- Slat 4 intermediate extend
- Slat 5 intermediate extend
- Slat 6 intermediate extend
- Slat 1 full extend
- Slat 2 full extend
- Slat 3 full extend
- Slat 4 full extend
- Slat 5 full extend
- Slat 6 full extend
- Flap 1 full extend
- Flap 2 full extend
- Flap 3 full extend
- Flap 4 full extend

A3-4 CONTROLS AND INDICATORS

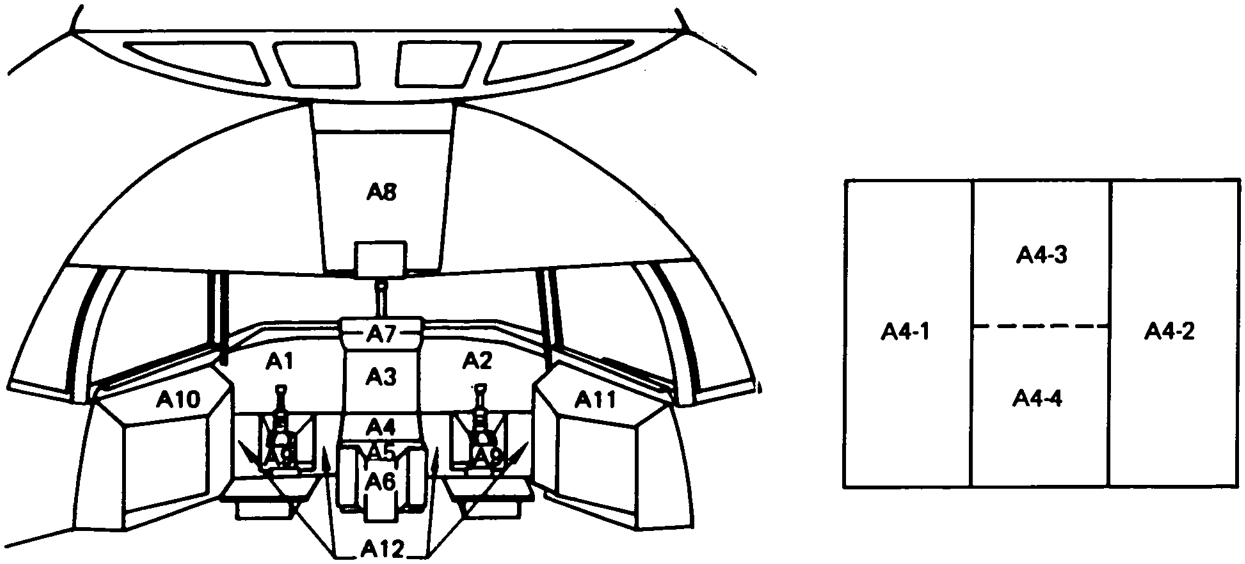
Display functions:

- Gear up
- Gear down
- Gear armed
- Gear off
- Autobrake maximum
- Autobrake minimum
- Autobrake off
- Autobrake inoperative
- Hydraulic brake pressure—system A
- Hydraulic brake pressure—system B
- Antiskid inboard off
- Antiskid outboard off
- Antiskid inboard inoperative
- Antiskid outboard inoperative

Control functions:

- Gear handle
- Gear arming
- Autobrake selector
- Antiskid inboard switch
- Antiskid outboard switch
- Override switch
- Horn cutout

Figure C-3. Pilot's Center Panel (A3) (Concluded)



A4-1/A4-2 MULTIFUNCTION KEYBOARDS (MFK)

Systems management:
- Communications
  - –VHF communication
  - –HF communication
  - –ACARS
  - –SELCAL
  - –Voice recorder
  - –Data link
- Navigation and advisory
  - –INS
  - –ADF
  - –ATC
  - –VHF NAV (VOR/ILS)
  - –MLS
  - –DME
  - –GPS
  - –Radio altimeter
  - –Marker beacon
  - –Flight recorder
  - –AIDS
  - –Data link
  - –GPWS
  - –Collision avoidance
    - TCAS
    - CDTI
  - –ACT fault status analysis
  - –ACT operations advisories
- Electrical
- Hydraulics
- Pneumatics
- Fuel and cg management
- Air-conditioning and pressurization
- Powerplant
- Ice and rain protection
- Air data
- APU
- Door control
- Weight and balance
- Landing gear and brakes
- Fire protection
- Flight controls
- Flight instruments and air data
- Audio, video, and flight recorders
- Planning and performance
- Checklists

Flight management:
- Initialization
- Navigation
  - –Initial position
  - –Horizontal
  - –Vertical
  - –Autotune
  - –Frequency scanning DME
  - –Flight plans
    - Active
    - Primary
    - Alternate
    - Automatic flight plan entry-data linking
    - Offset path
    - Course mode
    - Direct-to function

Figure C-4. Forward Electronic Control Panel (A4)

- Guidance
  - —Lateral
    - Desired track
    - Track error
    - Lateral profile, 2-D path
    - Deviation
    - Bearing to waypoint
    - Distance to waypoint
    - Limits—bank angle, roll rate
  - —Vertical
    - Deviation
    - Speed and altitude profile
    - Vertical profile, 3-D path
    - Limits—altitude, speed
    - Limits—alpha
  - —Thrust
    - Speed error
    - N1 (EPR)
    - Limits—N1, EPR
    - 4-D path/ground speed-time
    - N1 rating and derating
    - Flare retard
    - Alpha floor
    - Flap placard
- Performance management
  - —Vertical navigation flight profile
    - Takeoff
    - Climb
    - Cruise
    - Descent
    - Approach
  - —Performance parameters
    - CAS
    - Mach
    - Thrust setting (N1 or EPR)
    - Pitch attitude
  - —Performance modes (fuel- and time-efficient)
    - Takeoff
    - Climb
    - Cruise
    - Descent
    - Holding
    - Engine out
  - —Performance computations
    - Gross weight
    - Fuel
    - Range and endurance
    - Time
    - Performance policy factors
    - Flight index
    - Fuel mileage factor
    - Reduced climb thrust and step climb
    - Penalty functions
    - Performance monitoring
    - Data base
    - Windshear
- Performance data base
  - —Basic data
    - Thrust
    - Fuel flow
    - Drag polars
  - —Derived data
    - Climb speed
    - Cruise speed
    - Descent speed
    - Approach speed
- Navigation data base
  - —Radio station identifiers
  - —Airport identifiers
  - —Runway heading
  - —Runway threshold
  - —Company routes
  - —Transition routes
  - —Airways
  - —Alpha number waypoints
  - —SIDs
  - —STARs
  - —Profile descents
  - —ATC procedures
  - —Capacity—all U.S. airports
  - —Optimum mixing of IRS, DME, VOR, ILS, Omega, MLS, GPS
- Data entry
  - —Capable of quickly revising data without removing equipment from airplane
  - —Capable of revising data through CDU while maintaining status of original data base
  - —ARINC communication addressing and reporting system (ACARS)
  - —Data input and readout
  - —Mode-S data link
- Interface control
  - —Input data
  - —Output data
- Maintenance functions
  - —LRU BITE
  - —System test
  - —Fault detection failure isolation
  - —Status monitor and control
  - —ACT maintenance display interface (ACT preflight test initiate)

A4-3 COMMUNICATION AND NAVIGATION DISPLAYS AND CONTROLS

Display functions:

- Mode-S data link
- ACARS
- SELCAL
- VHF communication
- HF communication
- ATC transponder

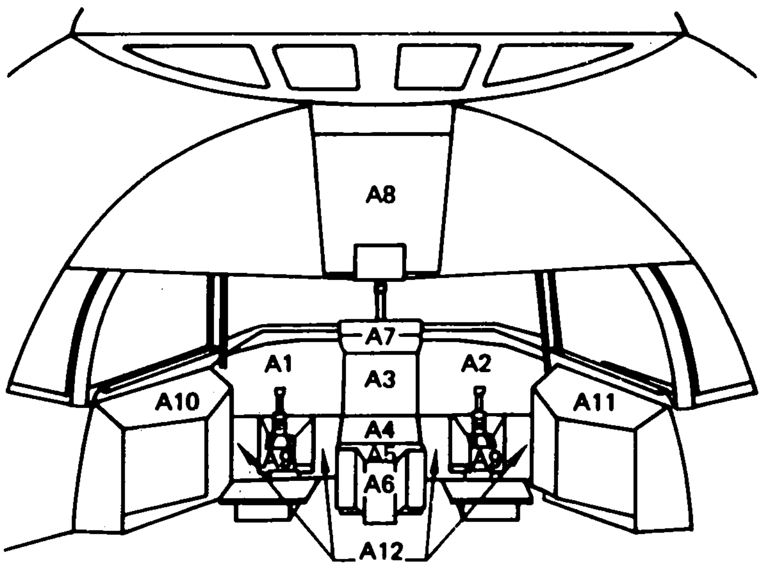
Figure C-4. Forward Electronic Control Panel (A4) (Continued)

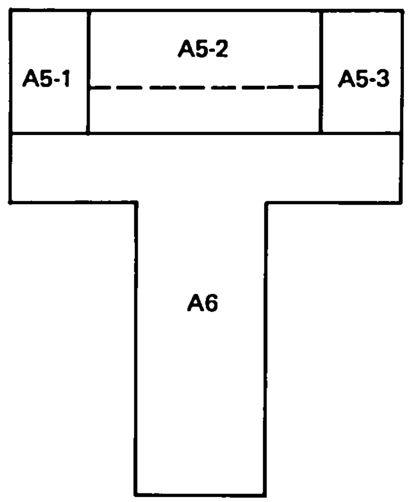
Control functions:
- Mode-S data link control
- ACARS control
- Transponder codes
- Identification

A4-4 CONTROLS AND INDICATORS

- Weather radar
  - –Gain
  - –Tilt
  - –Mode selector
    - Normal
    - Iso-echo

Figure C-4. Forward Electronic Control Panel (A4) (Concluded)





A5-1 CONTROLS AND INDICATORS

- Parking brake set and light
- Console lighting

A5-2 CONTROLS AND INDICATORS

- Electronic throttles
- Thrust reversers
- Speedbrakes
- Flaps

A5-3 CONTROLS AND INDICATORS

- Stabilizer trim control and indicator ("green band" trim range for takeoff)
- Aileron trim control and indicator
- Rudder trim control and indicator
- Stabilizer trim hydraulic shutoff

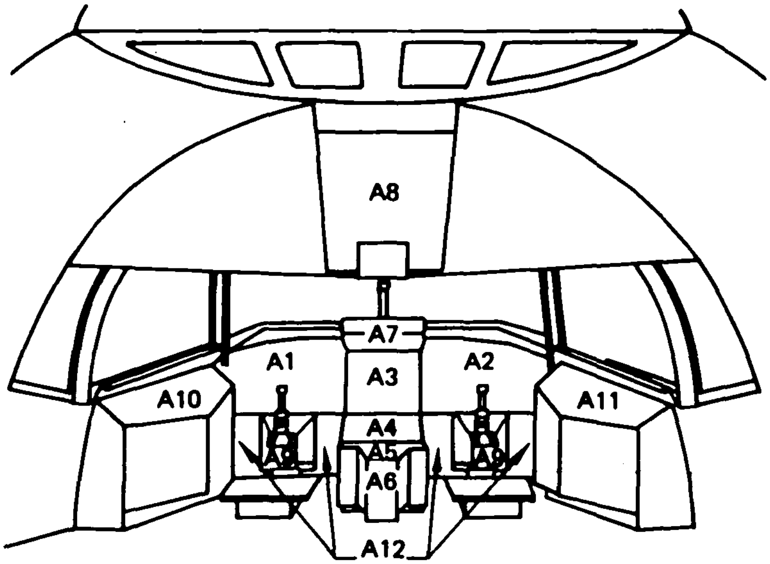
A5-4 CONTROLS AND INDICATORS

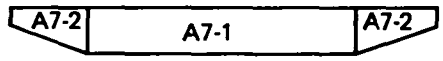
- Fuel and ignition

A6-1 MULTIFUNCTION KEYBOARD (MFK)

(Same as A4-1/A4-2 MFK)

Figure C-5. Control Stand (A5) and Multifunction Keyboard (A6)





A7-1 CONTROLS AND INDICATORS

Autopilot functions:

- Basic modes
  - —Attitude hold
  - —Attitude CWS
  - —Attitude select
  - —Velocity vector CWS
  - —Automatic trim
- Command modes
  - —Heading and track select
  - —Altitude select
  - —Airspeed select
  - —Vertical speed select
  - —Flightpath-angle select
  - —Go-around

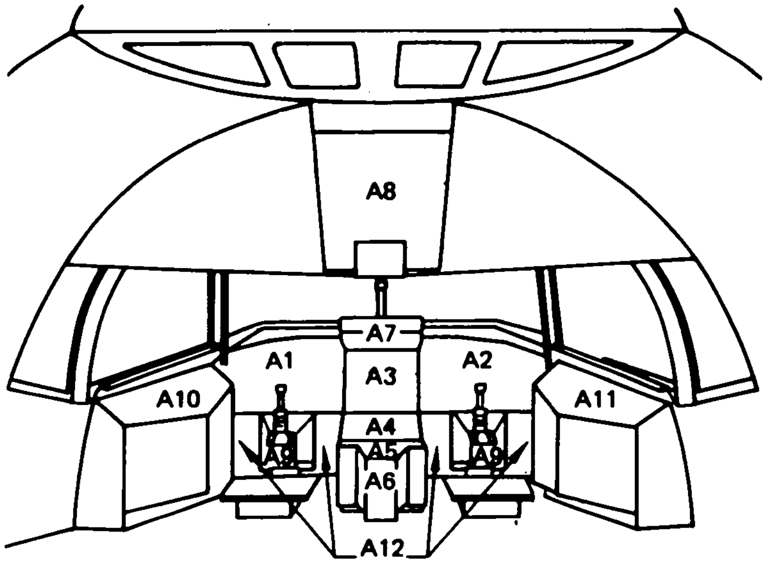
Autothrottle functions:

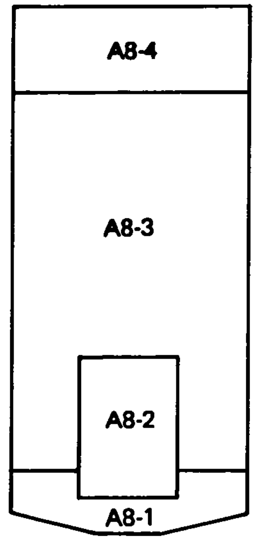
- Basic modes
  - —EPR/N1 hold
  - —N1/EPR limited airspeed hold
  - —N1/EPR limited vertical speed hold
  - —N1 rating and derating
- Command modes
  - —N1/EPR select
  - —Airspeed and Mach select
  - —Alpha floor
  - —Flap placard
- Extended outer loop modes
  - —Automatic landing
  - —Automatic rollout
  - —Back course approach
  - —Automatic guidance

A7-2 CONTROLS AND INDICATORS

- BCAS or time-critical display

Figure C-6. Automatic Flight Control System Control Panel (A7)





A8-1 **CONTROLS AND INDICATORS**
- Standby compass and light
- Console lights
- No Smoking lights
- Fasten Seat Belt lights
- Eye locator lights
- Wing lights
- Landing lights
- Beacon
- Navigation lights
- Runway turnoff lights
- Storm lights
- Windshield wiper
- Rain repellant
- Windshield wash

A8-2 **DISPLAYS AND CONTROLS**
- Engine and systems display
  (same as A3-1 and A3-2)
- ACT functions status—backup discretes
  - —PAS short
  - —PAS speed
  - —LAS
  - —AAL
  - —MLC
  - —GLA
  - —FMC

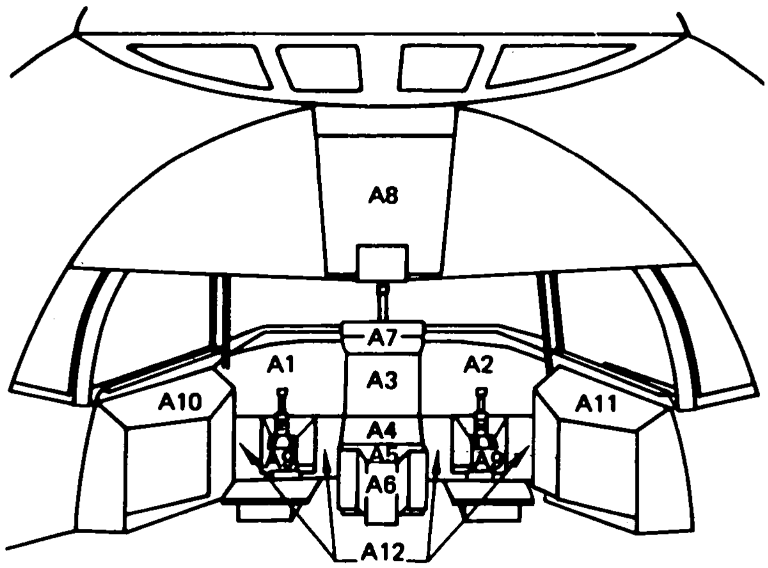
A8-3 **CONTROLS AND INDICATORS**
- Fire protection
  - —Engine 1 fire
  - —Engine 2 fire
  - —Engine 1 overheat
  - —Engine 2 overheat
  - —APU fire
  - —Wheel well fire
  - —Engine 1 fire test
  - —Engine 2 fire test
  - —Engine 1 overheat test
  - —Engine 2 overheat test
- Engine start
  - —Engine 1 ground start
  - —Engine 2 ground start
  - —Engine 1 flight start
  - —Engine 2 flight start
  - —Continuous ignition
- APU start
  - —APU start
  - —APU EGT
  - —APU overspeed
- Flight controls
  - —ACT emergency manual disconnect
  - —ACT reconnect
  - —LAS (replaces yaw damper)
  - —Alternate flaps
  - —Alternate LE slats
  - —Spoilers off
  - —Rudder emergency
  - —Rudder off
- Thrust reverser override
- Oxygen
  - —Emergency passenger oxygen
  - —Passenger oxygen on

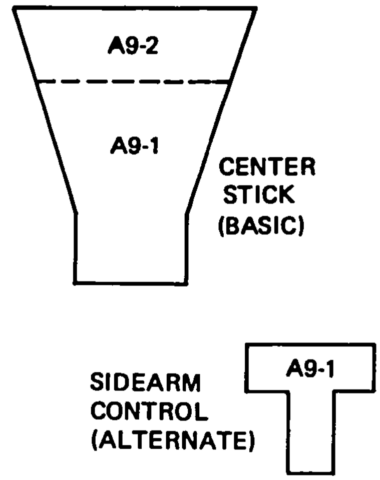
Figure C-7. Overhead Panel (A8)

- Pressurization
  - –Manual ac power control
  - –Manual dc power control
  - –Horn cutout
- Air-conditioning
  - –Passenger cabin temperature
  - –Passenger cabin temperature control
  - –Control cabin temperature control
- Electrical
  - –Generator 1 disconnect
  - –Generator 2 disconnect
  - –Battery switch
  - –Ground power switch
  - –dc voltage
  - –ac voltage
  - –ac frequency
  - –Ground power available
  - –Generator 1 on bus
  - –Generator 2 on bus
  - –Standby battery select
  - –APU generator on buses
- Emergency exit lights
- Cabin door release
- Service interphone
  - –Attendant call
  - –Ground call
  - –Call light
- Speaker
- FE interphone panel
- FE oxygen regulator
- Miscellaneous lighting controls

A8-4 CIRCUIT BREAKER PANEL

Figure C-7. Overhead Panel (A8) (Concluded)





A9-1 CONTROL FUNCTIONS–CENTER STICK (BASIC)

- Autopilot disconnect
- Pitch trim control
- Elevator and aileron control
- Interphone and radio microphone
- HUD mode select
- Stick shaker
- Stick pusher

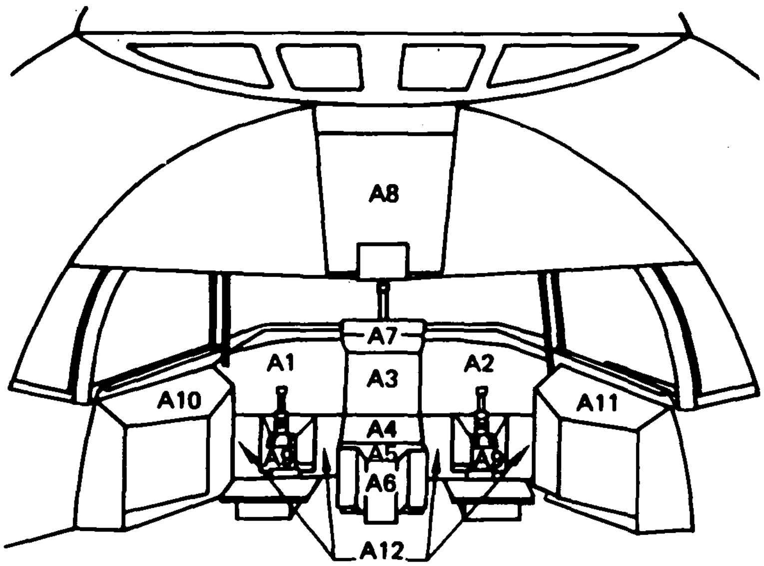
CONTROL FUNCTIONS–SIDEARM CONTROLLER (ALTERNATE)

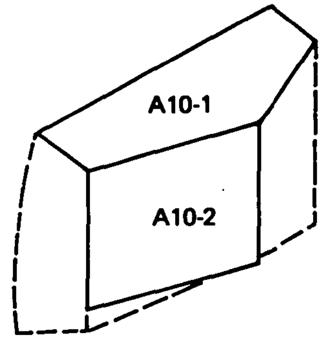
- Autopilot disconnect
- Pitch trim control
- Elevator and aileron control
- Interphone and radio microphone
- HUD mode select
- Stick shaker
- Stick pusher

A9-2 CURSOR CONTROL

- X, Y displacement

Figure C-8. Primary Stick Controllers (A9)





A10-1 CONTROLS AND INDICATORS

- Interphone
- Oxygen regulator
- Microphone and headset
- Miscellaneous lighting controls
- Worktable
- Coffee-cup holder
- Nosewheel steering wheel

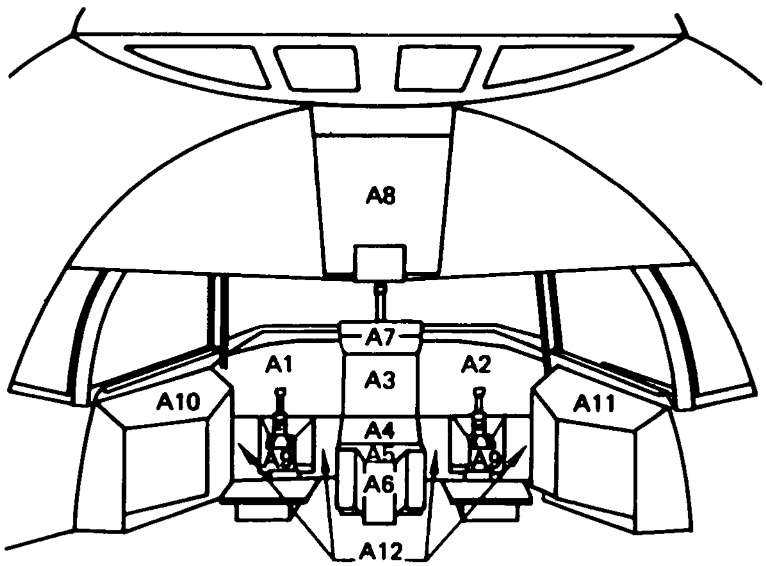
A10-2 STOWAGE AREA

- Maps
- Briefcase
- Performance manuals
- Portable oxygen bottle
- Hand ax
- First-aid kit
- Life vest
- Trash disposal

A11-1/A11-2 CONTROLS AND INDICATORS AND STOWAGE AREA

(Same as A10-1 and A10-2)

Figure C-9. Captain's Sidewall Panel (A10)



A12 CONTROLS AND INDICATORS

- Rudder
- Brakes
- Ground steering

A13 GLARESHIELD-MOUNTED CONTROLS AND INDICATORS (PILOT AND FIRST OFFICER)

- Gasper air control
- Miscellaneous lighting controls

Figure C-10. Steering and Braking Control (A12)

REFERENCES

C-1 Force, R. D. Functional Requirements for TCV Update TRA-102. D6-48644TN, Boeing Commercial Airplane Company, NASA Contract NAS1-13267, December 1979.

APPENDIX D: CRITICALITY AND RELIABILITY ASSESSMENT OF UNITS

APPENDIX D: CRITICALITY AND RELIABILITY ASSESSMENT OF UNITS

This appendix includes the criticality and reliability requirement assessment of units within the ACT avionics system architecture, as shown in Table D-1.

Table D-1. Criticality and Reliability Requirement Assessment of Units

Unit	Consequence of unit failure	Function criticality	Function reliability requirement	Unit criticality/ desired reliability	Remarks
Pilot flight controls (PFC)	• Unable to procure full-authority control on airplane dynamics and engines	A	$< 10^{-9}$	A/$< 10^{-9}$	
Dedicated pitch gyros (DPG)	• Unable to stabilize short-period longitudinal mode based on pitch rate and pilot's control column deflection	A	$< 10^{-9}$	A/$< 10^{-9}$	
Wing motion sensors (WMS)	• Unable to relieve gust and maneuver loads (wing-load alleviation)	B	10^{-4}	B/$< 10^{-4}$	
Radio altimeter	• Unable to provide low-range terrain clearance data (radio altitude), warning signals, and decision height information • Significantly degrades performance of autoland system	B	10^{-4}	B/$< 10^{-5}$	• Failure of radio altimeter would disable all major functions of the ground-proximity warning system if installed • Decision height information is critical in Category II and III autoland
Body motion sensors (BMS)	• Partially disable pitch control characteristic modification	B	10^{-3} to 10^{-4}	B/$< 10^{-5}$	Body motion sensors provide body acceleration and angular rate
	• Disable roll-yaw axis stability augmentation (LAS)	B	10^{-3} to 10^{-4}		
	• Disable angle-of-attack limiting	B	$< 10^{-4}$		
	• Partially disable wing-load alleviation	B	10^{-4}		
	• Disable attitude, roll, and pitch displaying	B	$< 10^{-5}$		
	• Partially disable pilot-assisted steering	C	10^{-3}		
	• Partially disable flight parameter capturing and maintaining	C	10^{-3}		
	• Partially disable landing system path capturing and tracking	B	$< 10^{-4}$		
	• Partially disable the flight augmentation system, flight guidance system, and flight management system				

Table D-1. Criticality and Reliability Requirement Assessment of Units (Continued)

Unit	Consequence of unit failure	Function criticality	Function reliability requirement	Unit criticality/ desired reliability	Remarks
Air data sensors (ADS)	• Probably unable to—				
	• Modify pitch control characteristics	B	10^{-3} to 10^{-4}	B/< 10^{-7}	
	• Modify roll control characteristics	B	10^{-3} to 10^{-4}		
	• Modify yaw control characteristics	B	10^{-3} to 10^{-4}		
	• Augment stability—pitch axis, short (enhanced mode)	B	10^{-3} to 10^{-4}		
	• Augment stability—pitch axis, speed	B	10^{-3} to 10^{-4}		
	• Limit angle of attack	B	$< 10^{-4}$		
	• Degraded performance in—				
	• Relief of structural load	B	10^{-3} to 10^{-4}		
	• Display of airspeed, Mach No., altitude, vertical speed	B	10^{-6} to 10^{-9}		
	• Capturing and maintaining flight parameters	C	10^{-3}		
	• Pilot-assisted steering	C	10^{-3}		
	• Augmenting stability in roll-yaw axis (LAS)	B	10^{-3} to 10^{-4}		
Surface position sensors (SPS)					
• Rudder sensors	• Unable to display rudder position	C	$< 10^{-3}$	B/10^{-4}	
• Elevator sensors	• Unable to display elevator position	C	10^{-3}		
	• Perform pilot-assisted steering	C	10^{-3}		
	• Capture and track landing system path	B	10^{-4}		
	• Augment stability—pitch axis, speed	B	10^{-4}		
• Aileron sensors	• Unable to display aileron positions	C	$< 10^{-3}$		
• Flaperon sensors	• Degraded performance in—				
	• Modifying pitch control characteristics	B	10^{-3} to 10^{-4}		
	• Modifying roll control characteristics	B	10^{-3} to 10^{-4}		
	• Augmenting stability in roll-yaw axis	B	10^{-3} to 10^{-4}		
	• Limiting angle of attack	B	$< 10^{-4}$		
	• Capturing and maintaining flight parameters	C	10^{-3}		
• Spoiler sensors	• Unable to display spoiler positions (speedbrake on/off indication)	C	10^{-3}		
• Stabilizer sensors	• Difficult to trim stabilizer effectively	C	10^{-3}		
• Stick sensor		C	10^{-3}		

Table D-1. Criticality and Reliability Requirement Assessment of Units (Continued)

Unit	Consequence of unit failure	Function criticality	Function reliability requirement	Unit criticality/ desired reliability	Remarks
Transponder	• Unable to continuously provide altitude and identity information (and possibly Mode-S message information in the future) to and from ground station	C	10^{-3}	C/10^{-4}	Generally, altitude, identity, and message information can be provided for the ground station via VHF communication at the expense of increased flight-crew workload
VOR/DME	• Unable to provide bearing and distance information relative to ground station (transmitters) • Degrades performance of flight management system and flight guidance system to achieve maximum economy	B	10^{-3} to 10^{-4}	B/10^{-4}	Failure of VOR/DME may force a mission restriction
Instrument landing system (ILS)	• Unable to provide information showing deviation from the established glide slope and runway centerline (localizer) • Disables autoland system (and part of the ground proximity warning system if installed)			B/$< 10^{-5}$	• Failure of ILS under bad weather conditions would usually force airplane to land at alternate airport with good visibility • The ILS becomes crucial in final stages of Category III autoland
Microwave landing system (MLS)	• Unable to measure deviation from runway centerline and minimum glide slope distance from the MLS station, azimuth, and elevation angles relative to it • Partially degrades performance of automatic navigation function of the flight management system in MLS coverage areas • Disables autoland system (and part of the ground proximity warning system if installed)			B/$< 10^{-5}$	The MLS becomes crucial when Category III autoland is performed
Autothrottle actuator	• Unable to eliminate differences between desired and actual thrust in autoflight mode • Partially unable to capture and maintain flight parameters	C	10^{-3}	C/$< 10^{-3}$	

Table D-1. Criticality and Reliability Requirement Assessment of Units (Continued)

Unit	Consequence of unit failure	Function criticality	Function reliability requirement	Unit criticality/ desired reliability	Remarks
Fuel sensors (FS)	• Unable to measure fuel flow and quantity remaining in fuel tanks • Marginally degrades the capabilities of the flight management system to achieve maximum economy			C/$< 10^{-3}$	Failure of fuel sensors may force flightcrew to periodically compute actual fuel remaining or check fuel remaining against a precomputed burn chart
Pneumatic sensors (PS)	• Unable to provide status of airbleeds or demand on engine system from pneumatic systems • Unable to automatically determine limit mode thrust settings	C	10^{-3}	C/$< 10^{-3}$	
Engine sensors (ES)	• Unable to measure engine pressure ratio, RPM of rotors, gas temperature, etc. • Partially disables (degrades) flight guidance system			B/$< 10^{-4}$	When maximum EPR (thrust) is exceeded under certain conditions, engine overheating, reduced engine life, and/or increased probability of failures are possible
Air data processor (ADP)	• Unable to provide accurate airspeed, Mach number, and altitude data • Loss or degraded performance of all major functions provided by the flight augmentation and autoflight system • Partially unable to capture and maintain flight parameters			B/$< 10^{-5}$	Assumes processor groups have capability to interpret raw air data from air data sensors in a degraded mode

Attitude processor (AP)	• Unable to provide accurate airplane attitude and true heading
	• Partially disables—
	  • Display attitude, pitch, and roll direction
	  • Pilot-assisted steering
	  • Capture and maintain flight parameters
	  • Capture and track landing system path
	  • Flight management system
	  • Flight guidance system
	  • Autoland system
				B/$< 10^{-4}$	Precise attitude and heading information are critical to flight in night and poor weather conditions

Table D-1. Criticality and Reliability Requirement Assessment of Units (Continued)

Unit	Consequence of unit failure	Function criticality	Function reliability requirement	Unit criticality/ desired reliability	Remarks
Major displays (head-up display, attitude director display, flight instrument display, horizontal situation display, engine display, system display)	• Unable to indicate conditions of flight, engine and system, etc.	C to B	10^{-3} to 10^{-7}	B/$< 10^{-8}$	
Major control panels (autoflight control panel, communication, navigation status panel, multifunction panel)	• Unable to select— • Automatic flight modes • Frequencies of communication and navigation radios • Desired performance modes • Initialize navigation system	 C B C C	 10^{-4} $< 10^{-5}$ 10^{-4} $< 10^{-4}$	B/$< 10^{-5}$	
Flight essential processor group (FEPG)	• Unable to perform— • Basic pitch control • Basic roll control • Basic yaw control • Basic short-period pitch stability	 A A B A	 10^{-9} 10^{-9} 10^{-7} 10^{-9}	A/$< 10^{-9}$	
Flight augmentation processor group (FAPG)	• Unable to perform— • Pitch control characteristic modification • Roll control characteristic modification • Yaw control characteristic modification • Enhanced short-period pitch stability • Speed mode pitch stability • Roll-yaw stability • Angle-of-attack limiting • Wing-load alleviation • Automatic flight control commands • Pitch trim • Disable autoland and flight guidance system	 B B B B B B B B C B	 10^{-3} to 10^{-4} 10^{-3} to 10^{-4} 10^{-3} to 10^{-4} 10^{-3} to 10^{-4} 10^{-3} to 10^{-4} 10^{-3} to 10^{-4} $< 10^{-4}$ $< 10^{-4}$ $< 10^{-3}$ $< 10^{-4}$	B/$< 10^{-7}$	

Table D-1. Criticality and Reliability Requirement Assessment of Units (Concluded)

Unit	Consequence of unit failure	Function criticality	Function reliability requirement	Unit criticality/ desired reliability	Remarks
Autoland processor group (ALPG)	• Unable to perform— • Autoflight attitude control • Autoflight rudder control • Autoflight (stabilizer) trim offload • Autoland path guidance			B/$<10^{-5}$	The ALPG becomes crucial when Category III autoland is performed
Flight guidance processor group (FGPG)	• Unable to perform— • Autoflight thrust control • Parameter guidance • Minimum speed and maximum speed limiting • Flight plan guidance • Limit thrust computation	C B B C C	10^{-3} 10^{-4} 10^{-4} 10^{-3} 10^{-3}	B/$<10^{-4}$	
Flight management processor group (FMPG)	• Unable to obtain— • Flight route definition • Flight profile optimization • Flight profile prediction • Automatic navigation • Navigation data • Performance data	C	10^{-3}	C/10^{-4}	
Sensor data bus	• Disable— • Flight augmentation systems • Major displays (including speed and altitude) • Autoland system • Flight guidance system • Flight management system			A/$<10^{-9}$	
Management data bus	• No access to— • Autoflight control panel • Communication and navigation status panel • Multifunction panel	C B C	10^{-3} 10^{-4} 10^{-3}	B/$<10^{-5}$	
Autoflight data bus	• No access to major system status display			B/$<10^{-4}$	
Actuation data bus				B/$<10^{-7}$	

Page

APPENDIX E: CREW PROCEDURAL FUNCTION TASK ANALYSIS

APPENDIX E: CREW PROCEDURAL FUNCTION TASK ANALYSIS

This appendix defines the system functions required to be performed in an Active Controls Technology (ACT) configured airplane. Functional flow diagrams (figs. E-1 and E-2) are carried through the second level, which defines major functional requirements. The crew procedural functions in Table E-1 are, in effect, the third-level functional requirements. The task analysis approach was used to determine the tasks the flightcrew will be required to perform to successfully complete a typical ACT airplane flight.

Throughout the appendix, the first-level flow diagram divides the flight into ten flight segments. The second-level flow diagram defines the major functions required of the flightcrew. Analysis begins with the third-level system functions, which relate directly by number and name with those functions derived from the functional flow block diagram. Each procedural function is divided into related crew action required to perform the task and information requirements at that task level.

A determination of criticality was made for each crew procedural function. The criticality assessment is based on the four categories of criticality. Criticality as defined here is different from—and not to be confused with—integrated caution and warning alerting system terminology. Criticality is concerned with an airplane's airworthiness or basic ability to fly, in contrast with pilot alerting to degraded modes. The categories are defined by the letters A through D as follows:

- Flight crucial (A)
- Flight critical (B)
- Workload relief (C)
- Dispatch critical (D)

Control locations associated with crew actions are based on the control and display functions presented in Appendix D. Display locations refer to the specific display or the

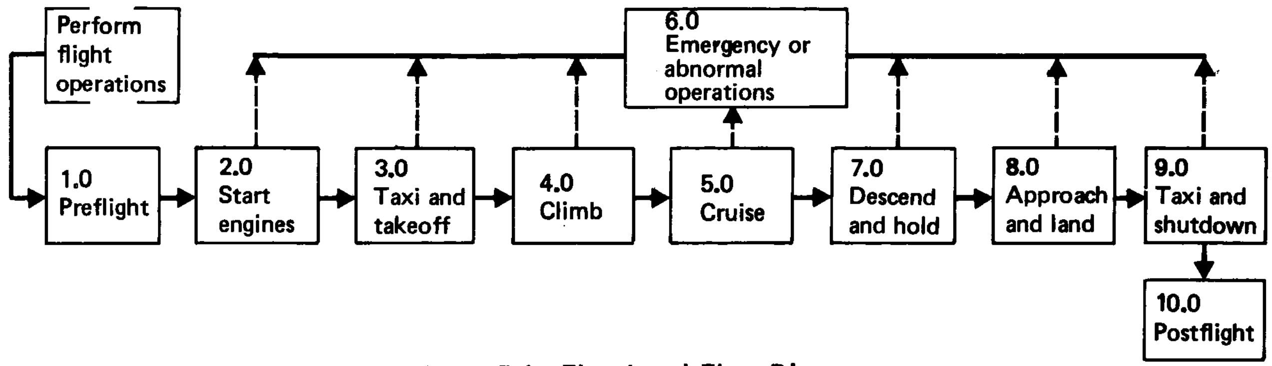


Figure E-1. First-Level Flow Diagram

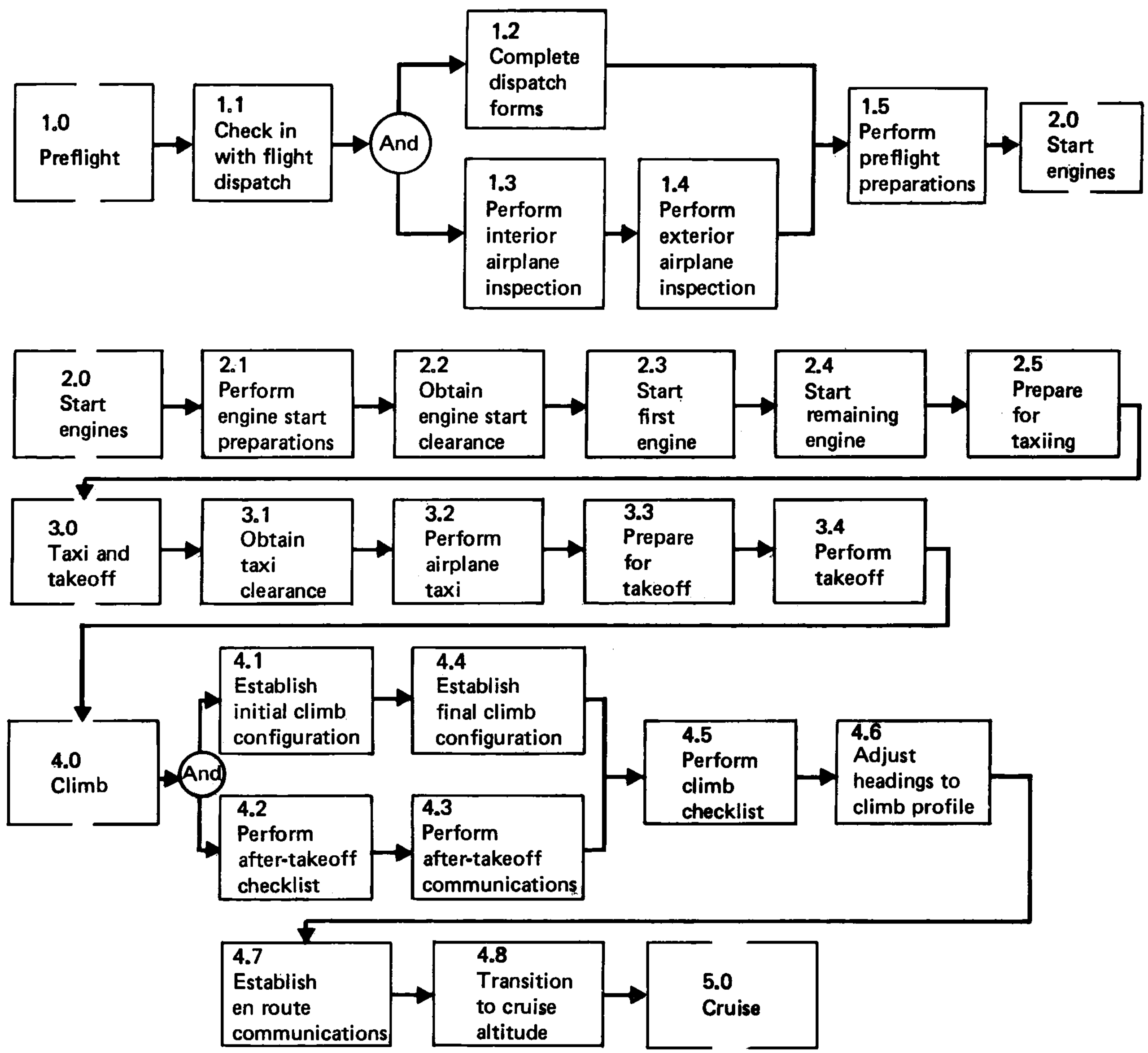


Figure E-2. Second-Level Flow Diagram

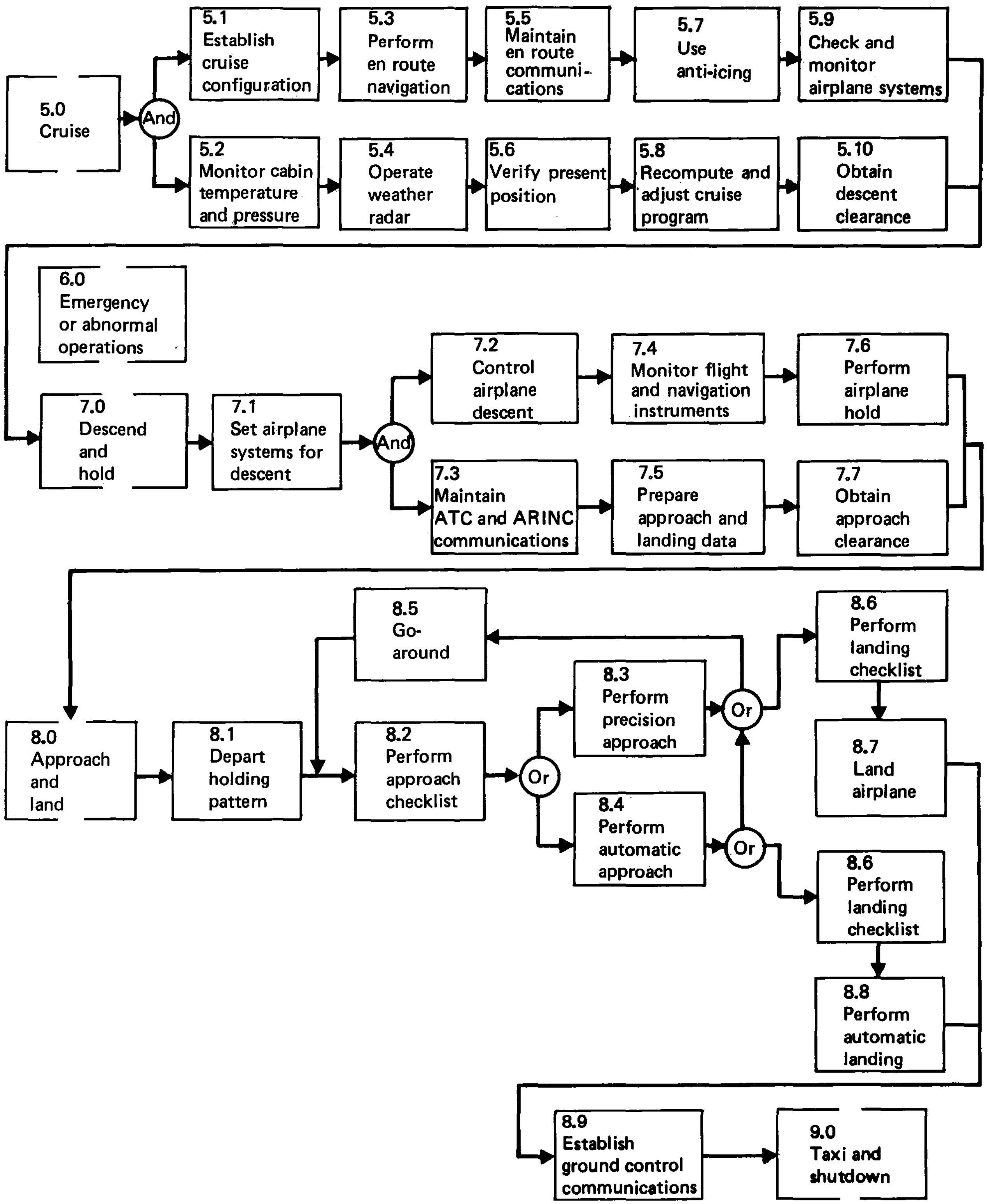


Figure E-2. Second-Level Flow Diagram (Continued)

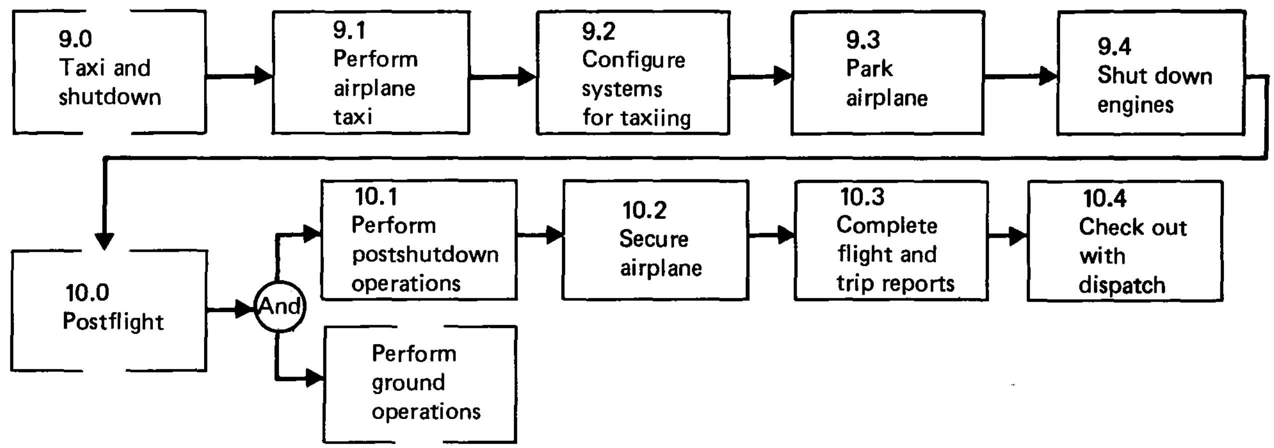


Figure E-2. Second-Level Flow Diagram (Concluded)

panel location in the case of a dedicated display or annunciation. The display identifiers are as follows:

- Aircrew alert system (AAS)
- Autoflight control panel (ACP)
- Secondary airspeed display (AD)
- Electronic attitude director indicator (EADI)
- Communication and navigation status panel (CNSP)
- Control surface position display (CSPD)
- Engine display (ED)
- Electronic horizontal situation indicator (EHSI)
- Head-up display (HUD)
- Multifunction display (keyboard display) (MFD)
- Radio magnetic display (RMD)
- System display (SD)
- Time-critical display (TCD)
- Vertical situation display (VSD)
- Windshield (Wshld)

To facilitate the definition of system functions, the following ground rules were applied:

- The mission profile and scenario establish the boundary conditions of the analysis.
- The block diagram layouts are meant to connote functional rather than time relationships.
- The functions derived do not attempt to describe how they are accomplished.
- The system functions are based on the Initial ACT Airplane Configuration (refs E-1 and E-2).
- The integrated system configurations are based on the supposition that an all-electronic airplane will be practicable by the 1990s.
- For crew systems planning, the airplane will have a two-person cockpit.

Pilot roles are defined conventionally; i.e., the captain has the ultimate authority and has primary control of the airplane, while the first officer monitors the flight progress and manages the systems at the captain's discretion.

REFERENCES

E-1 Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project—Initial ACT Configuration Design Study. Final Report. NASA CR-159249, July 1980.

E-2 Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project—Initial ACT Configuration Design Study. Summary Report. NASA CR-3304, October 1980.

Table E-1. Crew Procedural Functions (Page 1 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
2.0	START ENGINES					
2.1	PERFORM ENGINE START PREPARATIONS					
2.1.1	Set Airplane Systems for Engine Start	D	1. Turn left and right main tank fuel boost pumps on 2. Observe indications of boost pump operation 3. Open fuel crossfeed 4. Turn ATDP hydraulic pump off	A8-3 A3-2 A8-3 A8-3	1. Fuel boost pump switch position 2. Fuel pressure 3. Fuel valve position 4. ATDP hydraulic pump operation	A8-3 SD A8-3 SD A8-3 SD
2.1.2	Verify Airplane is Ready for Departure	D	1. Receive "Ready to Taxi" report from cabin attendants 2. Receive "Doors closed and secured" from ground crew 3. Observe absence of door warning annunciation 4. Verify landing gear down lock pins removed by ground crew 5. Verify all window heat on	Verbal Verbal A1-5 A2-4 Verbal A8-3	1. Absence of door warning annunciation 2. Window heat operation	AAS SD A8-3
2.1.3	Perform "Before Start Checklist"	--	1. Select before start checklist 2. Read checklist challenge 3. Respond to challenge	A4-2 A4-2 Verbal	1. Checklist items 2. Items complete 3. Recall of remaining items	MFD MFD MFD
2.2	OBTAIN ENGINE START CLEARANCE					
2.2.1	Obtain Clearance from Ground Crew	D	1. Select cabin/service interphone	A10-1	1. Selected microphone function	A10-1

Table E-1. Crew Procedural Functions (Page 2 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
			2. Contact ground crew for start clearance 3. Receive and acknow-ledge clearance	Verbal Aural Verbal	2. Start clearance	Aural
2.2.2	Obtain Clearance from Ground Control	D	1. Select ground control frequency 2. Contact ground control for start clearance 3. Acknowledge clearance	A4-3 Verbal Verbal	1. Frequency 2. Start clearance (data link message)	CNSP Verbal (MFD)
2.3	START FIRST ENGINE					
2.3.1	Complete Engine Start Preparation	D	1. Turn beacon lights on 2. Verify engine and system displays set for engine start 3. Turn galley power off 4. Verify APU bleed air open 5. Verify air-conditioning packs closed 6. Verify duct pressure within limits	A8-1 A3-1 A3-2 A8-3 A3-2 A3-2 A3-2	1. Beacon light switch position 2. Engine display format 3. System display format 4. Galley power switch position 5. APU bleed air valve position 6. Pack valve position 7. Duct pressure	A8-1 ED SD A8-3 SD SD SD
2.3.2	Start No. 2 Engine	B	1. Direct air pressure to No. 2 engine 2. Provide fuel and ignition to No. 2 engine 3. Monitor and report N2 RPM 4. Monitor and report engine oil pressure 5. Monitor fuel flow 6. Monitor EGT	A8-3 A5-4 A3-1 A3-1 A3-1 A3-1	1. Duct pressure 2. Fuel and ignition switch position 3. N2 RPM 4. Oil pressure 5. Fuel flow 6. EGT	SD A5-4 ED ED ED ED

Table E-1. Crew Procedural Functions (Page 3 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
2.3.3	Verify Normal Operations of No. 2 Engine	D	1. Verify No. 2 engine-driven hydraulic pump operation normal 2. Verify No. 2 engine instruments stabilized and normal 3. Verify No. 2 engine generator voltage and frequency within limits	A3-2 A3-1	1. Hydraulic pressure 2. EPR 3. N1 RPM 4. N2 RPM 5. Fuel flow 6. EGT 7. Oil pressure 8. Voltage 9. Frequency	SD ED ED ED ED ED ED SD SD
2.4	START REMAINING ENGINE					
2.4.1	Start No. 1 Engine	B	Repeat Functions 2.3.2 and 2.3.3 for No. 1 engine			
2.4.2	Supply Engine Generator Power to Main AC Buses	D	1. Close No. 1 and No. 2 generator control breakers 2. Verify generator No. 1 and No. 2 CSD oil temperature within limits	A8-3 A3-2	1. State of generator control breakers 2. CSD oil temperatures	A8-3 SD
2.4.3	Supply Transformer Rectifier (TR) Power to Main DC Buses	D	1. Verify voltage on main dc buses in limits 2. Verify voltage on ACT dc buses in limits 3. Verify voltage on battery buses in limits 4. Verify voltage to all four ACT channels 5. Verify battery charger operation normal	A3-2 A3-2 A3-2 A3-2 A1-5 A2-4	1. Main dc bus voltages 2. ACT dc bus voltages 3. Battery bus voltages 4. ACT channel voltages 5. Absence of battery charger fail annunciation	SD SD SD SD AAS

Table E-1. *Crew Procedural Functions (Page 4 of 53)*

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
2.4.4	Set Anti-Icing Controls	D	1. Verify pitot heat on 2. Turn on engine anti-ice (if icing conditions exist)	A3-2 A8-3	1. Pilot heat operation 2. Engine anti-ice operation	SD SD
2.4.5	Shut Down APU	D	1. Turn off APU	A8-3	1. Monitor indications of shutdown	SD AAS
2.5	PREPARE FOR TAXIING					
2.5.1	Set Fuel Panel for Takeoff	D	1. Turn on all main tank and structural tank boost pumps 2. Verify crossfeed valve closed	A4-2 A4-2	1. State of boost pumps 2. Crossfeed valve position	SD SD
2.5.2	Activate Air-Conditioning System	D	1. Open all bleed air valves 2. Verify pneumatic duct pressure normal 3. Close APU bleed air valve 4. Open pack valves	A4-2 A3-2 A4-2 A4-2	1. Engine bleed air valve positions 2. Pneumatic duct pressure 3. APU bleed air valve position 4. Pack valve positions	SD SD SD SD
2.5.3	Check and Set Hydraulic System for Normal Operation	D	1. Set ATDP hydraulic pump for automatic operation 2. Verify brake accumulator within pressure limits 3. Verify hydraulic quantity pressure and temperature normal	A8-3 A3-2 A3-2	1. State or mode of ATDP hydraulic pump 2. Brake accumulator pressure 3. Hydraulic quantity 4. Hydraulic pressure 5. Hydraulic fluid temperature	A8-3 SD SD SD SD
2.5.4	Perform "Before Taxi Checklist"	--	1. Select before taxi checklist 2. Read checklist challenge 3. Respond to challenge	A4-2 A4-2 Verbal	1. Checklist items 2. Items completed 3. Recall of remaining items	MFD MFD MFD

Table E-1. Crew Procedural Functions (Page 5 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
3.0	<u>TAXI AND TAKEOFF</u>					
3.1	OBTAIN TAXI CLEARANCE					
3.1.1	Verify Airplane Ready for Taxi	--	1. Request ground crew remove wheel chocks 2. Verify wheel chocks removed and all ground equipment disconnected and removed 3. Verify all doors closed	Verbal Verbal A3-2 A3-2 A2-4	1. Wheel chocks removed 2. Equipment disconnected 3. Doors closed	Aural Aural AAS Aural
3.1.2	Obtain Taxi Clearance from Ground Crew	D	1. Select cabin/service interphone 2. Contact ground crew for taxi clearance 3. Receive and acknowledge taxi clearance	A10-1 Verbal Aural Verbal	1. Selected microphone function 2. Taxi clearance	A10-1 Aural
3.1.3	Obtain Taxi Clearance from Ground Control	D	1. Select ground control frequency 2. Contact ground control for taxi clearance 3. Acknowledge clearance	A4-3 Verbal Verbal	1. Frequency 2. Taxi clearance (data link message)	CNSP MFD
3.1.4	Lock Cabin Door	--	1. Lock cabin door	--	1. Cabin door unlocked annunciation not displayed	AAS
3.2	PERFORM AIRPLANE TAXI					
3.2.1	Verify Normal Operation of Hydraulic Brake System	D	1. Depress brake pedals 2. Verify parking brake released	A12 A5-1	1. Parking brake released 2. Hydraulic brake pressure	A5-1 AAS SD AAS

Table E-1. Crew Procedural Functions (Page 6 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
			3. Release brake pedals 4. Verify hydraulic brake pressure normal	A12 A1-5 A3-2		
3.2.2	Taxi from Gate to Runway	D	1. Review alerting display and system annunciators for "go" condition 2. Control airplane speed using thrust levers and brakes 3. Maintain airplane direction using nose wheel steering 4. Turn on taxi light (as required)	A7-2 A1-5 A2-4 A5-2 A12 A10-1 A8-1	1. No annunciation to prevent taxi 2. Airspeed (taxi speed) 3. Taxiway markings 4. Taxi light switch position	AAS EADI HUD Wshld A8-1
	Note: The following tasks normally will be accomplished while taxiing					
3.2.3	Set Flaps for Takeoff	D	1. Set flaps to takeoff position 2. Verify flap position indication in agreement with selected setting 3. Verify stabilizer trim set for takeoff and in "green band"	A5-2 A3-3 A5-2 A5-3	1. Flap setting 2. Flap position 3. Stabilizer trim setting 4. Green band range	A5-2 CSPD A5-3 A5-3
3.2.4	Check Flight Instrument Response	D	1. Observe flight instruments working properly	A1 A2	1. Attitude 2. Heading 3. Field elevation 4. Present position 5. No fault annunciation	EADI EHSI RMD VSD EHSI AAS

Table E-1. Crew Procedural Functions (Page 7 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
3.2.5	Verify Proper Engine Operation	D	1. Check engine display for normal engine operation	A3-1	1. EPR 2. N1 RPM 3. N2 RPM 4. EGT 5. Fuel flow 6. No fault annunciation	ED ED ED ED ED AAS
3.2.6	Pressurize Airplane	D	1. Set pressurization system to "flight" 2. Observe system operation and information	A8-3 A3-2	1. Pressurization mode 2. Cabin altitude 3. Differential pressure 4. Pack status 5. Bleed status	A8-3 SD SD SD SD SD
3.2.7	Check Flight Controls	D	1. Verify full aileron control movement 2. Verify full elevator control movement 3. Hold nose wheel steering and verify full rudder control movement	A9-1 A9-1 A10-1 A12	1. Controls free 2. No obstruction	-- --
3.2.8	Obtain Flight Clearance	D	Note: May be accomplished prior to start of taxi 1. Set clearance delivery frequency 2. Request ATC clearance 3. Monitor clearance instruction 4. Acknowledge clearance 5. Obtain hard copy print	A4-3 Verbal A4-2 A8-2 A9-1 A11-1	1. Frequency 2. Data link clearance 3. Confirmation of acknowledgment 4. Hard copy	CNSP MFD CNSP --
3.3	PREPARE FOR TAKEOFF					
3.3.1	Verify Systems Set for Takeoff	D	1. Recheck attitude director display	A1-1 A2-1	1. Pitch 2. Roll	EADI EADI

Table E-1. Crew Procedural Functions (Page 8 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
			2. Recheck horizontal situation display 3. Recheck engine display 4. Set system display for takeoff 5. Recheck radios set for takeoff 6. Review alerting display 7. Unstow head-up display and verify set for takeoff	A1-2 A2-2 A3-1 A3-2 A8-2 A4-3 A1-5 A2-4 A1-3 A2-3	3. Airspeed 4. Altitude 5. Heading 6. Flight plan route (map) 7. Engine parameters 8. Takeoff systems 9. Radio frequencies 10. Current faults or advisories 11. HUD takeoff symbology	EADI EADI EHSI EHSI ED SD CNSP AAS HUD
3.3.2	Review Takeoff Briefing	--	1. Verify both pilots understand takeoff and departure procedures	--	1. Flight plan data 2. Flight plan route (map)	MFD EHSI
3.3.3	Perform Pretakeoff Challenge	D	1. Set tower frequency 2. Request takeoff clearance 3. Receive and acknowledge takeoff clearance	A4-3 Verbal Aural	1. Frequency	CNSP
3.3.4	Complete Takeoff Preparation		1. Set engine ignition (start) switches for takeoff 2. Activate Mode-S ATC transponder	A5-4 A4-2	1. Engine ignition switch position 2. Mode-S ATC transponder state	A5-4 CNSP
3.3.5	Taxi to Takeoff Position	D	1. Release parking brake (if set) 2. Control airplane with thrust levers, nose wheel steering, and brakes 3. Taxi to takeoff position	A5-1 A5-2 A10-1 A12 --	1. Parking brake released 2. Runway centerline	A5-1 AAS Wshld

Table E-1. Crew Procedural Functions (Page 9 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
			4. Align airplane with run-way	A12 A10-1		
3.4	PERFORM TAKEOFF					
3.4.1	Apply Takeoff Power	A	1. Control thrust	A5-2	1. EPR 2. EPR reference 3. Engine parameters	ED ED ED
3.4.2	Accelerate to Rotate Speed	B	1. Control airplane heading with rudder pedals 2. Hold control stick forward 3. Call "V1" and "Rotate"	A12 A9-1 Verbal	1. Heading 2. Runway centerline 3. Airspeed	HUD EADI HUD Wshld HUD AD
3.4.3	Rotate Airplane	A	1. Increase pitch 2. Control airplane	A9-1 A9-2 A12	1. Attitude 2. Flight path 3. Airspeed 4. Positive rate of climb	HUD EADI HUD HUD AD VSD
3.4.4	Retract Landing Gear	D	1. Call "Gear Up" 2. Raise landing gear	Verbal A3-4	1. Hydraulic fluid quantity 2. Gear position	SD AAS SD AAS
4.0	<u>CLIMB</u>					
4.1	ESTABLISH INITIAL CLIMB CONFIGURATION					
4.1.1	Trim Airplane	C	1. Adjust stabilizer trim 2. Adjust rudder trim 3. Adjust aileron trim	A9-1 A5-3 A5-3	1. Stabilizer, rudder, and aileron trim position 2. Airplane attitude 3. Control surface position	A5-3 EADI CSPD

Table E-1. Crew Procedural Functions (Page 10 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
4.1.2	Adjust Power Setting for Initial Climb	C	1. Set thrust levers or autothrottles	A5-2 A7-1	1. Reference EPR for selected climb profile 2. EPR 3. N1 EPR	MFD ED ED
4.1.3	Adjust Flight Path Angle To Maintain Climb Speed	C	1. Adjust flight path angle	A9-1	1. Flight path angle 2. Potential flight path angle 3. Airspeed 4. Center of gravity	EADI EADI AD
4.1.4	Retract Flaps at Required Speeds	--	1. Retract flaps per schedule	A5-2	1. Airspeed 2. Flap position	AD CSPD
4.1.5	Engage Autopilot	C	1. Engage autopilot for 4-D navigation	A7-1	1. Autopilot mode 2. Command speed 3. Command flight path angle 4. Command track angle	ACP ACP ACP ACP
4.1.6	Turn Off Engine Ignition Switches	--	1. Turn off engine ignition switches	A5-4	1. Switch position off	
4.2	PERFORM AFTER TAKE-OFF CHECKLIST					
4.2.1	Perform After Takeoff Checklist	--	1. Select after takeoff checklist 2. Read checklist challenge 3. Respond to challenge	A4-2 A4-2 Verbal	1. Checklist items 2. Items completed 3. Recall of remaining items	MFD MFD MFD
4.3	PERFORM AFTER TAKE-OFF COMMUNICATIONS					
4.3.1	Monitor Tower Frequency	D	1. Listen for advisory information 2. Respond to directions as appropriate	Aural --	None	

Table E-1. Crew Procedural Functions (Page 11 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
4.3.2	Communicate With Passengers (as desired)	--	1. Select PA 2. Communicate with passengers via headset	A10-1 Verbal	1. PA "in use" 2. Selected microphone function	A10-1 A10-1
4.3.3	Contact Departure Control	D	1. Select departure control frequency 2. Make initial contact communication	A4-3 Verbal	1. Frequency 2. Data link message	CNSP MFD
4.3.4	Accept Clearance		1. Monitor clearance instructions 2. Acknowledge clearance	A8-2 Verbal	1. Data link message 2. Hard copy	MFD A11-1
4.3.5	Inform ARINC of Off Time	C	1. ACARS sends time automatically after takeoff	A4-3	1. Annunciation of ACARS message being sent	
4.3.6	Monitor TCAS Display	C	1. Scan TCAS display for threat alerts	A7-2	1. Collision avoidance warning and maneuver instructions	TCS
4.4	ESTABLISH FINAL CLIMB CONFIGURATION					
4.4.1	Monitor Engine Performance	D	1. Cross-check engine instruments 2. Adjust thrust to climb EPR	A3-2 A5-2	1. Reference EPR 2. Computed climb EPR 3. Engine performance EPR N1 N2 Fuel flow	ED MFD ED
4.4.2	Trim Airplane to Climb EPR Conditions	C	1. Automatic with autopilot engaged	--	1. Aircraft attitude 2. Stabilizer, rudder, and aileron trim positions	EADI A5-3

Table E-1. Crew Procedural Functions (Page 12 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
4.4.3	Monitor Fuel System	D	1. Check fuel quantity for burnoff 2. Check engine fuel balance 3. Check fuel status	A3-2 A3-1 A6-1	1. Fuel quantities Right main Left main Right structural Left structural 2. Engine fuel flow 3. Fuel required 4. Total fuel remaining	SD ED MFD MFD
4.4.4	Set Anti-Ice Controls	--	1. Engine and wing anti-ice off (unless required) 2. Confirm probe heat and window heat on	A6-1 A8-2	1. Anti-ice operation 2. Probe heat operation 3. Window heat operation	SD SD SD
4.4.5	Monitor Cabin Pressure	D	1. Check cabin pressure system for proper cabin altitude and differential pressure	A8-2	1. Cabin altitude 2. Differential pressure	SD SD
4.4.6	Radio Altimeter Off	--	1. Automatic at 762m (2500-ft) AGL	--	1. Advisory if altimeter remains on	AAS
4.4.7	No Smoking and Fasten Seat Belt Signs Off	--	1. Switch off signs	A8-1	1. Switch positions	A8-1
4.4.8	Shut Down APU	D	1. Close APU bleed air 2. Shut off APU	A8-3 A8-3	1. Bleed air valve position 2. APU operation	A8-3 SD A8-3 SD
4.4.9	Don Oxygen Masks per FAA Requirements	D	1. Don oxygen mask 2. Select normal	A10-1 A10-1	1. Oxygen flow indicator	A10-1
4.4.10	Monitor CSD Oil Temperature	--	1. Observe CSD oil temperature normal	A3-2	1. CSD oil temperature	SD

Table E-1. Crew Procedural Functions (Page 13 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
4.4.11	Maintain Outside Visual Surveillance	--	1. Maintain continuous visual surveillance for other aircraft	Wshld	None	--
4.4.12	Monitor Flight Instruments	B	1. Monitor all flight instruments for proper setup and normal indications	A1	1. Attitude 2. Flight path 3. Airspeed 4. Altitude 5. Heading 6. Position	EADI EADI AD VSD EHSI EHSI
4.4.13	Set Barometric Pressure to Standard Setting	--	1. Call approaching transition altitude 2. Set standard pressure, 1013.2 mbar (29.92 inHg), passing transition altitude	Verbal A4-1 A4-2	1. Altitude 2. Transition altitude 3. Pressure setting	EADI VSD VSD VSD
4.5	PERFORM CLIMB CHECKLIST					
4.5.1	Perform Climb Checklist	--	1. Read checklist challenge 2. Respond to challenge	A4-2 Verbal A4-2	1. Checklist items 2. Items completed 3. Recall of remaining items	MFD MFD MFD
4.6	ADJUST HEADINGS TO CLIMB PROFILE					
4.6.1	Radar Vectors to Flight Plan Routing	C	1. Set vectored heading or turn using CWS to vectored heading 2. Select bank angle	A7-1 A7-1	1. Selected heading 2. Airplane heading	ACP ACP EHSI
4.6.2	Continue Climb per Flight Plan and ATC Instructions	C	1. Engage four-dimensional navigation when cleared flight plan route	A7-1	1. Autoflight mode 2. Command speed 3. Command flight path angle 4. Command track angle	ACP ACP ACP ACP

Table E-1. Crew Procedural Functions (Page 14 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
			2. Monitor airplane following flight director commands to maintain flight plan	A1-1 A1-2	5. Command altitude	ACP
4.6.3	Monitor Top of Climb Transition	C	1. Monitor altitude arc to meet any restrictions 2. Monitor altitude capture	A1-2 A2-2 A1-5 A2-5	1. Command altitude 2. Reference altitude 3. Airplane altitude	ACP EADI VSD EADI
4.7	ESTABLISH EN ROUTE COMMUNICATIONS					
4.7.1	Contact ATC Center	D	1. Select ATC center frequency 2. Make initial contact communication 3. Monitor transponder ident	A4-3 Verbal A4-3	1. Frequency 2. Data link message 3. "Ident"	CNSP MFD CNSP
4.7.2	Inform Center on Reaching Cruise Altitude	--	1. Contact center with altitude or automatic via data link	Verbal	1. Reference altitude 2. Airplane altitude	EADI VSD EADI VSD
4.7.3	Inform ARINC on Reaching Cruise Altitude	--	1. Verify ACARS operational ACARS will provide or request the following data without crew assistance: ● Airplane ident ● GMT ● Altitude ● Airspeed ● Heading	A4-3	1. ACARS operation status	CNSP AAS

Table E-1. Crew Procedural Functions (Page 15 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location

			• Position
			• Weight and balance
			• Maintenance data
			  • Engines
			  • Hydraulic
			  • Electrical
			  • Pneumatics
			  • ACT
			• Fuel quantities			

4.8	TRANSITION TO CRUISE ALTITUDE					
4.8.1	Monitor Airplane Controls and Instruments for Proper Cruise Altitude Capture	C	1. Ensure cruise altitude is set in autopilot control panel 2. Ensure altitude capture mode engaged 3. Monitor instrument panels and observe airplane levels off at the preselected cruise altitude	A7-1 A7-1 A1	1. Command altitude 2. Autopilot mode 3. Reference altitude 4. Airplane altitude	ACP ACP EADI VSD EADI VSD
5.0	<u>CRUISE</u>					
5.1	ESTABLISH CRUISE CONFIGURATION					
5.1.1	Set Cruise Thrust	C	1. Verify acceleration to cruise Mach 2. Verify thrust set to computed cruise EPR	A4-1 A3-1	1. Optimum cruise Mach 2. Engine EPR 3. N1 RPM 4. N2 RPM	MFD ED ED ED

Table E-1. Crew Procedural Functions (Page 16 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
			3. Cross-check N1, N2, EGT, and fuel flow to verify cruise setting	A3-1	5. EGT 6. Fuel flow 7. Computed cruise EPR	ED ED MFD
5.1.2	Monitor Cruise Performance	--	1. Check airspeed 2. Check attitude and flight path 3. Check heading and position	A1-4 A1-1 A1-2	1. Airspeed 2. Attitude 3. Flight path angle 4. Heading 5. Present position	AD EADI EADI EHSI EADI EHSI MFD
5.2	MONITOR CABIN TEMPERATURE AND PRESSURE					
5.2,1	Verify Zone Temperature	--	1. Check temperature in each of the heating zones 2. Adjust temperature warmer or cooler as required 3. Check alerting system for any faults; i.e., overheat	A3-2 A4-2 A2-4	1. Temperature for each heating zone 2. System faults	SD AAS
5.2.2	Monitor Pressurization System	--	1. Check cabin vertical speed 2. Check cabin altitude 3. Check differential pressure	A3-2 A3-2 A3-2	1. Cabin vertical speed 2. Cabin altitude 3. Differential pressure	SD SD SD
5.3	PERFORM EN ROUTE NAVIGATION					

Table E-1. Crew Procedural Functions (Page 17 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
5.3.1	Navigate Via Flight Plan Routing	C	1. Set radios for auto-tuning 2. Set map display to desired scale 3. Monitor map display for position and heading	A4-3 A1-2 A2-2 A1-2 A2-2	1. Radio mode 2. Map scale 3. Airplane position 4. Flight plan route 5. Waypoints	CNSP EHSI EHSI EHSI EHSI
5.3.2	Monitor Progress from Waypoint to Waypoint	C	1. Select progress status on multifunction display Lateral	A4-1 A4-2	1. Present position 2. Distance to waypoint 3. Course to waypoint 4. Time to waypoint 5. Cross-track error 6. Airplane track 7. Drift angle 8. Planned time of arrival 9. Estimated time of arrival 10. Winds 11. True airspeed 12. Ground speed	MFD MFD MFD MFD MFD MFD MFD MFD MFD MFD MFD MFD
			Vertical		1. Altitude 2. Command altitude 3. Flight path angle 4. Command flight path angle 5. Vertical speed 6. Command vertical speed	MFD MFD MFD MFD MFD MFD
			Fuel		1. Fuel required 2. Fuel reserve 3. Fuel quantity calculated 4. Fuel quantity totalizer 5. Fuel used	MFD MFD MFD MFD MFD

Table E-1. Crew Procedural Functions (Page 18 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
5.3.3	Change Course to Out-of-Sequence Waypoint		1. Select active flight plan "direct" function 2. Enter out-of-sequence waypoint that can be entered as one of the following: ● VOR designator ● NDB designator ● Geographic reference point (intersections, etc.) ● Bearing and range ● Latitude/longitude ● Airport designator ● Lateral offset, km (mi) 3. Reconnect flight plan from out-of-sequence waypoint either directly or via additional waypoints	A4-2 A4-2 A4-2		
5.3.4	Navigate by Radio Nav Rather than INS/Map	--	1. Set VORTAC frequencies and verify 2. Set course selector to desired course 3. Select VOR-ADF to VOR 4. Navigate from backup horizontal situation display	A4-3 A1-4 A1-4 A1-4	1. VORTAC frequencies 2. Course 3. Mode of operation 4. Magnetic heading 5. Course deviation 6. Bearing to station	CNSP RMD RMD RMD RMD RMD
5.4	OPERATE WEATHER RADAR					

Table E-1. Crew Procedural Functions (Page 19 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
5.4.1	Monitor Radar for Storm Indication	C	1. Activate weather radar system to normal 2. Select for weather radar display on horizontal situation display 3. Set range to maximum scale 4. Adjust trace 5. Set antenna tilt to 0 deg 6. Select range as desired 7. Determine if deviation required	A4-4 A1-2 A1-2 A4-4 A4-4 A1-2 --	1. Weather radar mode 2. HSD mode 3. Range 4. Antenna tilt angle 5. Radar return (storm cells)	A4-4 EHSI EHSI A4-4 EHSI
5.4.2	Monitor for Landfall	C	1. Set weather radar for ground mapping 2. Select for weather radar display on horizontal situation display 3. Set range to maximum scale 4. Adjust antenna tilt down to optimize radar display 5. Adjust gain to optimium setting for terrain detail	A4-4 A1-2 A1-2 A4-4 A4-4	1. Weather radar mode 2. HSD mode 3. Range 4. Antenna tilt angle 5. Radar return (terrain detail)	A4-4 EHSI EHSI A4-4 EHSI
5.5	MAINTAIN EN ROUTE COMMUNICATIONS					
5.5.1	Receive Clearance Instructions from ATC	--	1. Note data link message alert light 2. Note transmitted ATC message as displayed on multifunction display 3. Obtain hard copy print of message 4. Send acknowledgment	A1-5 A2-5 A4-2 A11-1 A9-1	1. Alert of incoming message 2. Data link message 3. Confirmation of acknowledgment	AAS MFD CNSP

Table E-1. Crew Procedural Functions (Page 20 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
5.5.2	Message to Airline (Through ARINC) Prior to Descent	--	1. Verify ACARS operational 2. Set to company frequency on VHF comm 3. Send computer-prepared progress message 4. Request voice contact if required for special request or information	A4-3 A4-3 A4-2 A4-2	1. ACARS operational status 2. VHF frequency 3. Progress message can include: Airplane ident GMT Altitude Airspeed Heading Position Weight and balance Fuel quantities Maintenance data 4. Confirmation of message sent	CNSP AAS MFD CNSP
5.6	VERIFY PRESENT POSITION					
5.6.1	Check Present Position Over Known Geographic Point	--	1. Select INS update data page 2. Compare latitude/longitude of each system and note any major differences 3. Update or align INS if found in error 4. Tune VHF NAV to VOR station and cross-check with INS outputs for present position	A4-2 A4-2 A4-2 A4-3 A4-2	1. No. 1 INS position 2. No. 2 INS position 3. No. 3 INS position 4. Latitude/longitude of known geographic point 5. VHF NAV frequency	MFD MFD MFD MFD CNSP
5.7	USE ANTI-ICING					
5.7.1	Monitor Window Heat for Proper Operation	D	1. Verify left and right window heat on 2. Check system status on system display	A2-4 A3-2	1. Alert of inoperative system 2. Window temperature	AAS SD

Table E-1. Crew Procedural Functions (Page 21 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
5.7.2	Monitor Probe Heat	D	1. Verify left and right probe heat on 2. Check system status on system display	A2-4 A3-2	1. Alert of inoperative system 2. Probe temperature	AAS SD
5.8	RECOMPUTE AND ADJUST CRUISE PROGRAM					
5.8.1	Change Heading	C	1. Observe waypoint passage on horizontal situation display 2. Observe course change per INS RNAV 3. Select bank angle (if desired)	A1-2 A1-2 A7-1	1. Inbound course 2. Outbound course 3. Selected course 4. Trend vector	EHSI EHSI ACP EHSI
5.8.2	Check Cruise Performance	C	1. Select performance data cruise page 2. Check actual Mach versus command Mach 3. Check actual EPR versus command EPR 4. Check EPR versus N1/N2 and EGT	A4-2 A2-4 A4-2 A3-1 A4-2 A3-1	1. Command speed 2. Actual speed 3. Command EPR 4. Actual EPR 5. N1 RPM 6. N2 RPM 7. EGT	MFD ACP EADI AD MFD ED ED ED ED ED
5.8.3	Scan Flight Instruments	B	1. Observe Mach 2. Observe vertical speed 3. Observe altimeter 4. Observe attitude 5. Observe navigation data 6. Observe autopilot control	A1-4 A1-5 A1-5 A1-1 A1-2 A1-1 A7-1	1. Mach 2. Vertical speed 3. Altitude 4. Pitch attitude 5. Roll attitude 6. Present position 7. Next waypoint	AD VSD VSD EADI EADI EHSI EHSI

Table E-1. Crew Procedural Functions (Page 22 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
					8. Ground speed 9. Heading 10. Course 11. Lateral navigation 12. Vertical navigation 13. 4-D navigation	EHSI EHSI EHSI ACP ACP ACP
5.8.4	Scan Engine Instruments	B	1. Monitor EPRs 2. Monitor RPMs (N1/N2) 3. Monitor EGT 4. Monitor fuel flow 5. Monitor oil temperature, pressure, and quantity		1. EPR 2. N1 RPM 3. N2 RPM 4. EGT 5. Fuel flow 6. Oil temperature 7. Oil pressure 8. Oil quantity	ED ED ED ED ED ED ED ED
5.9	CHECK AND MONITOR AIRPLANE SYSTEMS					
5.9.1	Monitor Electrical System	B	1. Select electrical system for systems display 2. Verify both generators on line and CSD oil temperature in limits 3. Verify voltage on each bus in limits 4. Verify battery charger operation normal	A3-2	1. Generator status 2. CSD oil temperature 3. Main dc bus voltages 4. Main ac bus voltages 5. ACT dc bus voltage 6. Battery bus voltage 7. Battery charge	SD SD SD SD SD SD SD

Table E-1. Crew Procedural Functions (Page 23 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
5.9.2	Monitor Hydraulic System	B	1. Select hydraulic system for systems display 2. Check hydraulic pressure and fluid level for each system 3. Verify operation of engine-driven pumps (EDP) 4. Verify operation of electric-motor-driven pumps 5. Verify operation of air-turbine-driven pump (ATDP) 6. Verify brake accumulator pressure in limits	A3-2	1. System A pressure 2. System B pressure 3. System C pressure 4. System A fluid level 5. System B fluid level 6. System C fluid level 7. EDP status (systems A and C) 8. EMP status (systems A, B, and C) 9. ATDP status (system B) 10. Brake accumulator pressure	SD SD SD SD SD SD SD SD SD SD
5.9.3	Monitor Fuel System	B	1. Select fuel system for systems display 2. Verify fuel quantities in each tank and verify fuel balance 3. Compare "calculated fuel" with fuel totalizer and verify nearly same 4. Verify crossfeed valve closed 5. Verify operation of all fuel boost pumps	A3-2	1. Right main tank fuel quantity 2. Left main tank fuel quantity 3. Right structural tank fuel quantity 4. Left structural tank fuel quantity 5. Calculated fuel remaining 6. Fuel quantity totalizer 7. Crossfeed valve position 8. Fuel boost pumps status	SD SD SD SD SD SD SD SD

Table E-1. Crew Procedural Functions (Page 24 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
5.9.4	Monitor Pressurization System	B	1. Select pressurization system for systems display 2. Check cabin altitude and differential pressure per schedule 3. Check cabin vertical speed 4. Verify pneumatic duct pressure normal 5. Verify pack valves open 6. Verify bleed air valves set as required	A3-2	1. Cabin altitude 2. Differential pressure 3. Cabin vertical speed 4. Pneumatic duct pressure 5. Pack valve positions 6. Bleed air valve positions	SD SD SD SD SD SD
5.9.5	Monitor Flight Control (ACT) System	B	1. Select flight control system for systems display 2. Verify status of active controls: PAS short PAS speed LAS WLA FMC AAL (stall warning) 3. Verify status of control surfaces 4. Verify trim settings normal	A3-2 A3-3	1. PAS short status 2. PAS speed status 3. LAS status 4. WLA status 5. FMC status 6. AAL status 7. Position of control surfaces 8. Aileron trim position 9. Stabilizer trim position 10. Rudder trim position	SD SD SD SD SD SD CSPD A5-3 A5-3 A5-3
5.10	OBTAIN DESCENT CLEARANCE					

Table E-1. Crew Procedural Functions (Page 25 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
5.10.1	Receive Message from ATC Center	--	See Function 5.5.1		Clearance is for a low-profile approach to an ILS approach with a time restriction at the outer marker	
5.10.2	Plan Descent	C	1. Select flight plan route 2. Verify routing agrees with clearance 3. Input time restriction (PTA) in flight management computer 4. Observe that holding will be required	A4-2 A4-2 A4-2 A4-2	1. Flight plan route 2. Planned time of arrivals 3. Message that __ min holding required	MFD MFD MFD
5.10.3	Request ATC Clearance for Holding	--	1. Request holding from center	Verbal	1. Data link message from center–"Holding approved"	
5.10.4	Insert Holding in Flight Plan	C	1. Select flight plan route 2. Insert "hold" at holding fix 3. Review holding pattern and revise if necessary (standard pattern assumed) 4. Insert expected approach clearance time (holding fix ETA plus minutes of holding)	A4-2 A4-2 A4-2	1. Flight plan route 2. Holding fix 3. Holding fix ETA 4. Inbound holding radial 5. Turn direction 6. Turn direction 7. Leg time 8. Optimum hold speed 9. Leg distance 10. Fuel time remaining to reserves 11. Expected approach clearance	MFD MFD MFD MFD MFD MFD MFD MFD MFD MFD MFD

Table E-1. Crew Procedural Functions (Page 26 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
6.0	EMERGENCY AND ABNORMAL OPERATIONS (NOT PRESENTLY USED)					
7.0	DESCEND AND HOLD					
7.1	SET AIRPLANE SYSTEMS FOR DESCENT					
7.1.1	Check Anti-Ice Systems	D	1. Verify window heat on 2. Turn on wing anti-ice 3. Verify probe heat on 4. Turn on engine anti-ice	A2-4 A8-3 A2-4 A8-3	1. Alert of inoperative window and probe heat 2. Anti-ice systems operational status	AAS A8-3 SD
7.1.2	Monitor Fuel System		See Function 5.9.3			
7.1.3	Monitor Pressurization System		See Function 5.9.4			
7.2	CONTROL AIRPLANE DESCENT					
7.2.1	Descend to Holding Altitude	C	1. Monitor flight director commands for initiation of descent at top of descent (TOD) or	--	1. TOD point 2. Command altitude (holding altitude) 3. Command flight path angle 4. Altitude range prediction	EHSI ACP VSD ACP EHSI
			1. Select velocity vector CWS at TOD 2. Disengage autothrottle	A7-1 A7-1	1. TOD point 2. Autoflight mode 3. Autothrottle mode	EHSI ACP ACP

Table E-1. Crew Procedural Functions (Page 27 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
			3. Set flight path angle using altitude range prediction 4. Set throttles to match potential flight path 5. Monitor descent for level off 6. Use speed brakes if required to maintain airspeed	A9-1 A1-2 A5-2 A1-1 A1-1 A1-5 A5-2	4. Altitude range prediction 5. Flight path angle 6. Potential flight path 7. Altitude 8. Vertical speed 9. Speed brake position	EHSI EADI EADI EADI VSD CSPD
7.2.2	Monitor Systems	--	1. Monitor pneumatic duct pressure to determine minimum engine thrust 2. Monitor cabin rate of descent 3. Monitor engine performance 4. Monitor cg for ACT limits 5. Monitor cabin temperature and adjust if necessary	A3-2 A3-2 A3-1 A3-2 A8-3	1. Pneumatic duct pressure 2. Cabin vertical speed 3. EPR 4. N1 RPM 5. N2 RPM 6. EGT 7. Fuel flow 8. Center of gravity 9. Cabin temperature	SD SD ED ED ED ED ED SD A8-3
7.2.3	Establish Holding Configuration	C	1. Select holding performance page 2. Set holding speed in autoflight control panel 3. Level off at holding altitude 4. Select altitude hold 5. Set engine thrust to establish holding airspeed 6. Engage autothrottle	A4-2 A7-1 A9-1 A7-1 A5-2 A7-1	1. Type holding entry; i.e., left-right-teardrop 2. Optimum airspeed 3. Command speed 4. Altitude 5. Autoflight mode 6. EPR 7. Airspeed 8. Autothrottle mode	MFD MFD ACP VSD ACP ED AD ACP

Table E-1. Crew Procedural Functions (Page 28 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
7.3	MAINTAIN ATC AND ARINC COMMUNICATIONS					
7.3.1	Communicate with ATC Center	D	1. Advise departing cruise altitude 2. Confirm crossing holding fix and begin hold	Verbal Verbal	1. Center frequency 2. Present position 3. Holding fix position	CNSP EHSI EHSI
7.3.2	Perform Holding Pattern	D	1. Advise center of entering holding pattern 2. Receive acknowledgment from center 3. Receive clearance for low-profile descent 4. Send acknowledgment 5. Select ATIS for present weather data link 6. Obtain hard copy print of ATIS information	Verbal A4-2 A4-2 A9-1 A4-3 A11-1	1. Center frequency 2. Alert of incoming message 3. Data link messages 4. Confirmation of acknowledgment 5. ATIS frequency 6. ATIS information	CNSP AAS MFD CNSP CNSP MFD
7.4	MONITOR FLIGHT AND NAVIGATION INSTRUMENTS					
7.4.1	Monitor Inertial Navigation System	C	1. Select lateral (track) progress page of the multifunction display 2. Verify map display correlates with next waypoint data for position, heading, and time	A4-1 A1-2	1. Present position 2. Next waypoint 3. Cross-track error 4. Track	MFD EHSI MFD EHSI MFD EHSI MFD EHSI

Table E-1. Crew Procedural Functions (Page 29 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
					5. Drift 6. ETA 7. PTA 8. Distance to waypoint	MFD MFD MFD MFD EHSI
7.4.2	Utilize VOR Navigation	D	1. Tune VHF NAV to VOR 2. Set course selector on radio magnetic display 3. Monitor ADD and RMD for proper attitude and course displays	A4-3 A1-4 A1-1 A1-4	1. VHF NAV frequency 2. Selected course 3. Attitude 4. Bearing to VOR 5. DME distance to VOR 6. Course deviation	CNSP RMD EADI RMD RMD RMD
7.4.3	Maintain Surveillance for Other Aircraft	A	1. Visually scan outside for other aircraft in area (visibility permitting) 2. Monitor TCAS display for warning of possible collision threat	Wshld A7-2	1. Clearing 2. Threat alert warning 3. Maneuver command 4. Azimuth to threat 5. Range to threat	Wshld TCAS TCAS TCAS TCAS
7.4.4	Monitor Airspeed and Rate of Descent	B	1. Monitor Mach number 2. Cross-check airspeed indicators 3. Call altitudes during descents 4. Reset altimeters to local altimeter setting 5. Cross-check altimeters	A1-4 A2-4 A1-4 A2-4 A1-1 A2-1 A2-5 Verbal A1-5 A2-5 A1-5 A2-5	1. Mach number 2. Airspeed 3. Altitude 4. Altimeter setting	AD AD EADI VSD EADI VSD MFD

Table E-1. Crew Procedural Functions (Page 30 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
				A1-1 A2-1		
7.4.5	Maintain Radio Navigation	D	1. Set VHF NAV-2 for manual operation 2. Tune VHF NAV-2 to preceding VOR station 3. Set course selector to inbound course 4. Verify airplane on course 5. Observe station passage 6. Reset course selector to outbound course	A4-3 A4-3 A2-4 A2-4 A2-4 A2-4	1. VHF NAV mode 2. VHF NAV frequency 3. Selected course 4. Course deviation 5. Bearing to VOR 6. DME distance to VOR	CNSP CNSP RMD RMD RMD RMD
7.5	PREPARE APPROACH AND LANDING DATA					
7.5.1	Review Holding and Approach Information	--	1. Review and coordinate procedures for holding 2. Review expected approach clearance and procedures	A1-2 A4-1 A1-2 A4-2	1. Holding pattern (map) 2. Holding altitude 3. Holding speed 4. Holding leg time 5. Type entry turn 6. EAC 7. Approach routing (map) 8. Approach speeds 9. Missed approach procedures	EHSI MFD MFD MFD MFD MFD EHSI MFD MFD EHSI
7.5.2	Look Up and Record Landing Data	C	1. Select performance data for landing 2. Observe gross weight and cg 3. Confirm flap setting	A4-2	1. Gross weight 2. Center of gravity 3. Selected flap setting 4. Approach speed 5. Threshold speed	MFD MFD MFD MFD MFD

Table E-1. *Crew Procedural Functions (Page 31 of 53)*

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
			4. Observe reference speeds		6. Go-around speed	MFD
			5. Observe go-around EPR setting		7. Go-around EPR	MFD
			6. Obtain a hard copy print of landing data	A11-1		
			7. Verify crew responsibility for approach and landing	--		
7.6	PERFORM AIRPLANE HOLD					
7.6.1	Enter Holding Pattern	C	1. Observe station passage	A1-2	1. Holding fix position	EHSI
					2. Present position	EHSI
			2. Monitor entry turn on map display	A1-2	3. Holding pattern (map)	EHSI
7.6.2	Control Airplane in Holding Pattern	C	1. Monitor position for turn to capture the inbound course	A1-2	1. Holding fix position	EHSI
					2. Holding pattern (map)	EHSI
					3. Time	Clock
			2. Monitor course capture as airplane turns inbound	A1-2	4. Elapsed time	Clock
			3. Note time of course intercept and monitor airplane on inbound course	A1-5 A1-2		
7.6.3	Set ADF and VHF Course for Approach	D	1. Tune ADF receivers to outer marker frequency	A4-3	1. ADF frequencies	CNSP
					2. RMD modes	RMD
					3. ADF identifier	RMD
			2. Set first officer's RMD to ADF and observe identity and bearing toward the outer marker locations	A2-4	4. Bearing to ADF station	RMD
					5. VHF comm frequencies	CNSP

Table E-1. Crew Procedural Functions (Page 32 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
			3. Verify VHF communications frequencies are set for approach and land	A4-3		
7.6.4	Review and Update Landing Data	C	1. Review data on landing performance page of MFD 2. Verify landing gross weight and fuel with fuel status on the systems display 3. Verify fuel panel set for landing 4. Recheck final approach speed	A4-2 A4-2 A3-2 A3-2 A4-2	1. Landing gross weight 2. Center of gravity 3. Selected flap setting 4. Approach speed 5. Threshold speed 6. Go-around speed 7. Go-around EPR 8. Crossfeed valve position 9. Fuel boost pumps status 10. Fuel quantities 11. Fuel time remaining	MFD MFD MFD MFD MFD MFD MFD SD SD SD MFD SD
7.6.5	Review Instrument Approach Procedures	C	1. Select flight plan and review approach routing 2. Select approach for display on HSD and review approach plate 3. Check for radio aids required 4. Review field elevations minimum altitude and missed approach procedures	A4-2 A2-2 A2-2 A4-3 A4-2	1. Aproach procedures 2. Approach routing 3. Airspeed and altitudes 4. Approach minimums 5. Missed approach procedures 6. Radios tuned 7. Rate of descent 8. Field elevation	MFD EHSI MFD EHSI EHSI CNSP EHSI MFD
7.7	OBTAIN APPROACH CLEARANCE					

Table E-1. Crew Procedural Functions (Page 33 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
7.7.1	Monitor Approach Control	D	1. Receive final approach clearance via data link 2. Obtain hard copy print 3. Acknowledge clear-ance	A4-2 A11-1 A9-1	1. Alert of incoming message 2. Data link message 3. Confirmation of acknowledgment	AAS MFD CNSP
7.7.2	Verify Ready To Commence Approach		1. Verify captain and first officer both understand approach clearance 2. Adjust procedures and crew coordin-ation if required 3. Verify ready to commence approach	-- -- --	1. Hard copy of approach clearance	--
8.0	<u>APPROACH AND LAND</u>					
8.1	DEPART HOLDING PATTERN					
8.1.1	Monitor Departure from Holding Pattern	C	1. Monitor map for station passage at EAC time 2. Monitor automatic course change and observe outbound course is established 3. Retune VHF NAV No. 1 to ILS frequency and identify	A1-2 A1-2 A4-3	1. Present position 2. Holding fix 3. Outbound course 4. Trend vector 5. ILS frequency	EHSI EHSI EHSI EHSI CNSP

Table E-1. Crew Procedural Functions (Page 34 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
8.1.2	Communicate with Approach Control	D	1. Inform departure of holding pattern altitude 2. Receive acknowledgment 3. Receive data link message to slow to 93 m/s (180 kn) for increased separation 4. Send acknowledgment	A4-2 A4-2 A4-2 A9-1	1. Message to be sent 2. Confirmation of message sent 3. Data link message 4. Confirmation of acknowledgment	MFD CNSP MFD CNSP
8.1.3	Initiate Altitude Loss	C	1. Set command speed to 93 m/s (180 kn) 2. Set altitude select to outer marker altitude 3. Engage altitude capture 4. Monitor rate of descent	A7-1 A7-1 A7-1 --	1. Command speed 2. Selected altitude 3. Autoflight mode 4. Vertical velocity 5. Altitude range	ACP ACP ACP VSD EHSI
8.1.4	Lower Flaps to 2	B	1. Place flap selector to 2 2. Monitor flap position display	A5-2 A3-3	1. Inboard flap position 2. Outboard flap position 3. Leading edge flap positions	CSPD CSPD CSPD
8.1.5	Monitor Flight Instruments	--	1. Present position should show airplane outboard on course 2. Airspeed 93 m/s (180 kn), check speed error display 3. Observe range decrease to outer marker 4. Monitor rate of descent	A1-1 A1-1 A1-2 A1-5	1. Present position 2. Outboard course 3. Trend vector 4. Airspeed 5. Speed error 6. Range to fix 7. Vertical speed	EHSI EHSI EHSI EADI EADI EHSI VSD

Table E-1. Crew Procedural Functions (Page 35 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
8.1.6	Set Instruments for Approach	--	1. Select landing performance page 2. Observe data for completeness 3. Obtain hard copy print 4. Set airspeed and EPR references 5. Cross-check EPR settings and data card		1. Landing data 2. Approach speed 3. Threshold speed 4. Go-around EPR	MFD MFD AD MFD AD MFD ED
8.1.7	Start APU–Inflight Start	D	1. Verify APU fire protection available 2. Initiate APU start 3. Monitor APU system for normal start	A8-3 A8-3 --	1. APU mode 2. RPM initial rise 3. APU EGT 4. APU oil pressure 5. APU RPM	A8-3 SD SD SD SD
8.1.8	Activate Seat Belt Fastened and No Smoking Lights	D	1. Turn on "Fasten Seat Belts" lights 2. Turn on "No Smoking" lights	A8-1 A8-1	1. Seat belt light switch position 2. No smoking light switch position	A8-1 A8-1
8.1.9	Activate Radio Altimeters	--	1. Set captain and first officer decision height 2. Cross-check radio altitudes	A4-2 A1-1 A2-1 A1-5 A2-5	1. Decision height (selected) 2. Altitude (AGL)	A1-1 VSD EADI
8.1.10	Monitor Airplane Alerting System	B	1. Recall remaining faults for display	A2-4	1. Active faults	AAS
8.1.11	Activate Engine Ignition	--	1. Turn on continous engine ignition	A8-3	1. Engine ignition switch position	A8-3

Table E-1. Crew Procedural Functions (Page 36 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
8.1.12	Monitor Airplane Level Off at Outer Marker Altitude	B	1. Verify altitude select autoflight control panel 2. Monitor altitude capture initiation 3. Cross-check captured altitude with barometric altitude	A7-1 -- A7-1 A1-1 A1-5	1. Selected altitude 2. Airplane altitude 3. Vertical speed	ACP EADI VSD VSD
8.2	PERFORM APPROACH CHECKLIST					
8.2.1	Perform Approach Checklist	C	1. Select descent/approach checklist 2. Read checklist challenge 3. Respond to challenge	A4-2	1. Checklist items 2. Items completed 3. Recall of remaining items	MFD MFD MFD
8.3	PERFORM PRECISION APPROACH					
8.3.1	Lower Flaps to 5	B	1. Place flap selector to 5 2. Monitor flap position display	A5-2 A3-3	1. Inboard flap position 2. Outboard flap position 3. Leading edge flap position	CSPD CSPD CSPD
8.3.2	Set ILS Mode	C	1. Verify VHF NAV No. 1 set to ILS frequency 2. Verify VHF NAV No. 2 set to ILS frequency 3. Set pilot's radio magnetic display to VOR	A4-3 A4-3 A1-4	1. VHF NAV frequencies 2. Radio magnetic display (RMD) mode 3. ILS identifier	CNSP RMD RMD

Table E-1. Crew Procedural Functions (Page 37 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
8.3.3	Reduce Speed	--	1. Disengage autopilot and autothrottle 2. Slow to 88 m/s (170 kn) 3. Place flaps to 10 4. Monitor flap position 5. Slow to 82 m/s (160 kn) 6. Place flaps to 20 7. Monitor flap position	A9-1 A5-2 A5-2 A5-2 A3-3 A5-2 A5-2 A3-3	1. Autoflight modes 2. Airspeed 3. Flap position	ACP AD CSPD
8.3.4	Scan Flight Instruments		1. Scan instrument panel and center panel 2. Maintain desired airplane attitude 3. Verify desired configuration 4. Monitor aircrew alerting system for indication of instrument failures or discrepancies	A1/A2 A3 A1-4	1. Airplane attitude 2. Airspeed 3. Flight path angle 4. Heading/track 5. Altitude 6. Course deviation 7. Fault annunciation	EADI EADI EADI EADI EHSI EADI EHSI AAS
8.3.5	Scan Flight Systems	C	1. Monitor basic systems display 2. Monitor aircrew alerting system for alert of system abnormalities	A3-2 A1-5 A2-4	1. Cabin pressurization 2. Fuel status 3. System hydraulic pressures and quantities 4. Alerts for fault/failures ACT system Hydraulic power Electrical power Pressurization Air-conditioning Ice and rain protection Power plant Fuel	SD SD SD AAS

Table E-1. Crew Procedural Functions (Page 38 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
					Landing gear Flight controls Navigation equipment Autoflight systems Flight instruments APU	
8.3.6	Monitor Weather Radar	D	1. Observe weather radar periodically depending on meteorological conditions	A4-4	1. Weather returns 2. Land mass returns	EHSI EHSI
8.3.7	Maintain Visual	--	1. Pilot not flying maintains a visual search for other aircraft 2. Pilot not flying maintains a visual scan for changing weather conditions	Wshld Wshld	1. Other aircraft (traffic) 2. Weather conditions	-- --
8.3.8	Monitor Head-Up Display	C	1. Unstow and position head-up display if not previously in use 2. Monitor airplane attitude and control 3. Monitor localizer symbol for movement 4. Call "localizer alive" at first positive inward motion of the localizer symbol	A1-3 A1-3 A1-3 A1-3	1. Airplane attitude 2. Airspeed 3. Flight path angle 4. Heading/track 5. Altitude 6. Localizer 7. Glide slope	HUD HUD HUD HUD HUD HUD HUD
8.3.9	Intercept ILS Inbound Course	C	1. Monitor head-up display 2. Observe localizer symbol approach ILS course	A1-3 A1-3	1. Localizer symbol 2. Flight path angle 3. Selected course 4. Present position	HUD HUD HUD EHSI EHSI

Table E-1. Crew Procedural Functions (Page 39 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
			3. Turn airplane to intercept inbound course 4. Observe on head-up display that airplane is inbound on selected course 5. Verify localizer capture on horizontal situation displays	A9-1 A1-3 A1-2 A2-2	5. Trend vector 6. Attitude 7. Altitude 8. Airspeed 9. Heading/track	EHSI HUD HUD HUD HUD
8.3.10	Initiate Altitude Loss	--	1. Reduce thrust to maintain speed 2. Adjust flight path for desired rate of descent 3. Pilot not flying calls altitude, speed, rate of descent, and 30.5m (100 ft) above minimum 4. Level off at outer marker altitude	A5-2 A9-1 Verbal A9-1	1. EPR 2. Airspeed 3. Potential flight path 4. Flight path angle 5. Altitude 6. Vertical velocity 7. Altitude reference	ED HUD HUD HUD HUD VSD HUD
8.3.11	Reduce Speed	C	1. Slow to 69 m/s (135 kn) 2. Arm speed brake 3. Place flaps to 30 4. Monitor flap position	A5-2 A5-2 A5-2 A3-3	1. Airspeed 2. Flap position	HUD AD CSPD
8.3.12	Intercept Glide Slope	C	1. Monitor glide slope symbol on head-up display 2. Pilot not flying calls "glide slope alive" at first downward motion of glide slope symbol	A1-3 A1-3	1. Glide slope 2. Flight path angle 3. Potential flight path	HUD HUD HUD

Table E-1. Crew Procedural Functions (Page 40 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
			3. Adjust flight path angle to maintain glide slope 4. Adjust thrust to maintain airspeed	A9-1 A5-2		
8.3.13	Lower Landing Gear	B	1. Place landing gear in down position 2. Monitor gear down indication	A3-4 A3-4	1. Gear position	A3-4 AAS
8.3.14	Fly Instruments	C	1. Maintain speed and rate of descent 2. Call out significant deviations from present references 3. Maintain localizer and glide slope 4. Monitor alerting	A5-2 A9-1 -- A9-1	1. Airspeed 2. Flight path angle 3. Localizer deviation 4. Glide slope deviation 5. Alerts/faults	HUD HUD HUD HUD AAS
8.4	PERFORM AUTOMATIC APPROACH AND LANDING		Note: Many of the tasks in this function are repeats of the tasks involved in the precision approach. No elements are listed for repeated tasks.		Initial Conditions: • Airplane on intercept to ILS course • Descending to intermediate altitude	
8.4.1	Lower Flaps to 5		See Function 8.3.1			
8.4.2	Set ILS Mode		See Function 8.3.2			
8.4.3	Reduce Speed	--	1. Set command speed to 88 m/s (170 kn) 2. Place flaps to 10 3. Monitor flap position	A7-1 A5-2 A3-3	1. Autoflight modes 2. Command airspeed 3. Airspeed 4. Flap position	ACP ACP AD CSPD

Table E-1. *Crew Procedural Functions (Page 41 of 53)*

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
			4. Set command speed to 82 m/s (160 kn) 5. Place flaps to 20 6. Monitor flap position	A7-1 A5-2 A3-3		
8.4.4	Scan Flight Instruments		See Function 8.3.4			
8.4.5	Scan Flight Systems		See Function 8.3.5			
8.4.6	Monitor Weather Radar		See Function 8.3.6			
8.4.7	Maintain Visual Surveillance		See Function 8.3.7			
8.4.8	Monitor Head-Up Display		See Function 8.3.8			
8.4.9	Intercept ILS Inbound	C	1. Select autopilot "land" mode 2. Observe localizer symbol approach center position 3. Observe localizer annunciation, signifying localizer capture 4. Monitor airplane turn to intercept inbound course 5. Verify localizer capture on horizontal situation displays	A7-1 A1-3 A1-1 A1-2 A1-3 A1-2 A2-2	1. Autopilot mode 2. Localizer symbol 3. Flight path angle 4. Selected course 5. Present position 6. Trend vector 7. Attitude 8. Altitude 9. Airspeed 10. Heading/track	ACP HUD HUD HUD EHSI EHSI EHSI HUD HUD HUD HUD
8.4.10	Initiate Altitude Loss	C	1. Set command altitude to desired value 2. Engage altitude capture	A7-1 A7-1	1. Command altitude 2. Autoflight mode 3. Flight path 4. Altitude 5. Altitude reference	ACP ACP HUD HUD HUD

Table E-1. Crew Procedural Functions (Page 42 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
			3. Monitor descent and altitude capture	A1-3		
8.4.11	Reduce Speed	C	1. Set command speed to 69 m/s (135 kn) 2. Arm speed brake 3. Place flaps to 30 4. Monitor flap position	A7-1 A5-2 A5-2 A3-3	1. Autoflight mode 2. Command speed 3. Airspeed 4. Flap position	ACP ACP HUD AD CSPD
8.4.12	Intercept Glide Slope	C	1. Pilot not flying calls "glide slope alive" at first downward motion of glide slope symbol 2. Monitor glide slope until capture 3. Observe glide slope annunciation, signifying glide slope capture 4. Monitor airplane pitch to follow glide slope commands	A1-3 A1-3 A1-1 A1-3	1. Glide slope 2. Flight path angle 3. Potential flight path	HUD HUD HUD
8.4.13	Lower Landing Gear		See Function 8.3.13			
8.4.14	Monitor Flight Instruments	C	1. Monitor speed and rate of descent 2. Call out significant deviations from preset references 3. Monitor displays to ensure airplane follows localizer and glide slope commands	A1-3 A1-3 A2-3	1. Airspeed 2. Command airspeed 3. Flight path angle 4. Localizer deviation 5. Glide slope deviation 6. Alerts/faults	HUD HUD HUD HUD HUD AAS

Table E-1. Crew Procedural Functions (Page 43 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
			4. Monitor alerting system for critical parameters failures	A1-5 A2-4		
8.5	NOT USED					
8.6	PERFORM LANDING CHECKLIST					
8.6.1	Perform Landing Checklist	C	1. Select landing checklist 2. Read checklist challenge 3. Respond to challenge	A4-2 A4-2 Verbal A4-2	1. Checklist items 2. Items completed 3. Recall of remaining items	MFD MFD MFD
8.7	LAND AIRPLANE					
8.7.1	Cross Outer Marker	C	1. Observe outer marker symbol 2. Inform tower at outer marker 3. Receive clearance to land	A1-3 A9-1 Aural	1. Outer marker symbol 2. VHF frequency 3. Voice message from tower	HUD CNSP Aural
8.7.2	Maintain Flight Path During Glide Slope Descent	B	1. Disengage autopilot and autothrottle if not already done 2. Maintain localizer using aileron and rudder 3. Maintain airspeed (zero speed error) using throttles	A7-1 A5-2 A9-1 A12 A5-2	1. Autopilot mode 2. Localizer deviation 3. Attitude 4. Heading 5. Glide slope deviation 6. Flight path angle 7. Airspeed	ACP HUD HUD HUD HUD HUD HUD
8.7.3	Maintain Visual Observation for Runway	B	1. Maintain visual surveillance through head-up display	A1-3	1. Runway (synthetic runway should overlay visual runway)	Wshld

Table E-1. Crew Procedural Functions (Page 44 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
			2. Call out "runway in sight"	--		
8.7.4	Cross Middle Marker	C	1. Observe middle marker symbol 2. Make go-around decision based on visual contact at decision height	A1-3 Wshld	1. Middle marker symbol 2. Runway 3. Decision height 4. Altitude	HUD Wshld HUD HUD
8.7.5	Turn on Landing Lights	D	1. Switch on landing lights 2. Apply rain repellent as required	A8-1 A8-1	1. Landing light switch position	A8-1
8.7.6	Perform Flare and Touchdown	A	1. Monitor HUD for flare symbol and synthetic runway cue 2. Monitor radio altitude as crosscheck 3. Reduce thrust 4. Increase pitch attitude 5. Touchdown	A1-3 A1-3 A5-2 A9-1 --	1. Flare symbol 2. Synthetic runway 3. Radio altitude 4. Flight path 5. Attitude 6. Localizer deviation 7. Glide slope deviation	HUD HUD HUD HUD HUD HUD HUD
8.7.7	Perform Rollout	B	1. Maintain directional control with rudder 2. Maintain wings level with ailerons 3. Reduce thrust to idle 4. Observe auto speed brake position 5. Lower nose to runway with elevator 6. Apply wheel braking as required	A12 A9-1 A5-2 A3-3 A9-1 A12	1. Runway centerline 2. EPR 3. Speed brake position 4. Brake pressure 5. Thrust reverser position 6. Wiper switch position 7. Airspeed 8. Flap position	Wshld ED ED SD ED A8-1 HUD CSPD

Table E-1. Crew Procedural Functions (Page 45 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
			7. Display thrust reversers 8. Turn on wipers as required 9. Monitor speed until reduced to taxi speed 10. Return throttles to idle 11. Raise flaps to 25 or less	A5-2 A8-1 A1-3 A5-2 A5-2		
8.7.8	Runway Turnoff	B	1. Maintain directional control with rudder and nose wheel steering 2. Maintain speed with wheel brakes and thrust 3. Turn off runway	A12 A10-1 A12 --	1. Runway markings 2. Airspeed	Wshld HUD
8.8	PERFORM AUTOMATIC LANDING		Note: Many of the tasks in this function are repeats of the tasks involved in the manual land airplane. No elements are listed for repeated tasks.		Initial Conditions: ● Landing checklist completed ● Airplane is at outer marker and configured for landing ● Airplane is previously coupled to autoflight system for autoland (See Function 8.4)	
8.8.1	Cross Outer Marker		See Function 8.7.1			
8.8.2	Monitor Flight Path During Glide Slope Descent		1. Monitor localizer deviation 2. Monitor glide slope deviation	A1-3 A1-3	1. Autoflight mode 2. Localizer deviation 3. Glide slope deviation 4. Attitude	ACP HUD HUD HUD

Table E-1. Crew Procedural Functions (Page 46 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
			3. Monitor airspeed (zero speed error)	A1-3	5. Heading 6. Flight path angle 7. Airspeed 8. Synthetic runway	HUD HUD HUD HUD
8.8.3	Maintain Visual Observation for Runway		See Function 8.7.3			
8.8.4	Cross Middle Marker		See Function 8.7.4			
8.8.5	Turn on Landing Lights		See Function 8.7.5			
8.8.6	Monitor Flare and Touchdown	A	1. Monitor HUD for flare symbol and synthetic runway cue 2. Monitor radio altitude as crosscheck 3. Observe annunciation of flare capture 4. Monitor airplane touchdown and runway alignment 5. Verify throttles at idle and speed brake operation with wheel spin-up	A1-3 A1-3 A1-1 A1-3 A5-2	1. Flare symbol 2. Synthetic runway 3. Radio altitude 4. Flight path 5. Attitude 6. Localizer deviation 7. Glide slope deviation 8. EPR 9. Speed brake position 10. Runway centerline	HUD HUD HUD HUD HUD HUD HUD ED CSPD Wshld
8.8.7	Perform Rollout	B	1. Disengage autopilot 2. Apply wheel braking as required 3. Deploy thrust reversers 4. Turn on wipers as required 5. Monitor speed until reduced to taxi speed	A9-1 A12 A5-2 A8-1 A1-3	1. Brake pressure 2. Thrust reverser position 3. Wiper switch position 4. Airspeed 5. Flap position	SD ED A8-1 HUD CSPD

Table E-1. Crew Procedural Functions (Page 47 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
			6. Return throttles to idle 7. Raise flaps to 25 or less	A5-2 A5-2		
8.8.8	Runway Turn Off		See Function 8.7.8			
8.9	ESTABLISH GROUND CONTROL COMMUNICATIONS					
8.9.1	Contact Ground Control	D	1. Set VHF comm radio frequency to ground control 2. Request taxi and parking instructions 3. Receive clearance to taxi 4. Send acknowledgment 5. "ON" time is automatically transmitted via ACARS along with request for gate assignment 6. Receive gate assignment via ACARS	A4-3 Verbal	1. VHF comm frequency 2. Confirmation of acknowledgment 3. Alert of incoming message 4. Data link message	CNSP CNSP AAS MFD
9.0	TAXI AND SHUTDOWN					
9.1	PERFORM AIRPLANE TAXI					

Table E-1. Crew Procedural Functions (Page 48 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
9.1.1	Configure Airplane for Taxi	D	1. Turn off ignition switches 2. Raise speed brakes 3. Raise flaps	A5-4 A5-2 A5-2	1. Ignition switch position 2. Speed brake position 3. Flap position	A5-4 CSPD CSPD
9.1.2	Taxi to Gate Area	D	1. Maintain airplane directional control using rudder pedals and nose wheel steering 2. Maintain a safe taxi speed using thrust levers and wheel brakes 3. Monitor ground control 4. Maintain visual watch to avoid obstacles and other aircraft 5. Monitor alerting system for normal operation of systems	A12 A5-2 -- -- A1-5 A2-4		
9.2	CONFIGURE SYSTEMS FOR TAXIING					
9.2.1	Turn Off Anti-Icing Systems	D	1. Turn off probe heat 2. Turn off engine anti-ice 3. Turn off wing anti-ice 4. Turn off window heat	A8-3 A8-3 A8-3 A8-3	1. Probe heat switch position 2. Engine anti-ice switch position 3. Wing anti-ice switch position 4. Window heat switch position	A8-3 A8-3 A8-3 A8-3
9.2.2	Secure Radar, Transponder	D	1. Turn off weather radar 2. Turn off ATC transponder (operations of flight recorder and radar altimeter automatic)	A4-4 A4-3	1. Weather radar mode 2. ATC transponder mode	A4-4 CNSP

Table E-1. Crew Procedural Functions (Page 49 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
9.2.3	Supply Electrical Power from APU	D	1. Turn off galley power switches 2. Observe APU generator voltage and frequency 3. Close APU generator switch and open main generator switches	A8-3 A3-2 A8-3	1. Galley power switch position 2. APU generator voltage 3. APU generator frequency 4. Generator switch positions	A8-3 SD SD A8-3
9.2.4	Monitor Engine Instruments	D	1. Observe engine instrument indications normal	A3-1	1. EPR 2. N1 RPM 3. N2 RPM 4. EGT 5. Fuel flow	ED ED ED ED ED
9.2.5	Set Fuel System for Taxi	D	1. Turn off one fuel pump in each main tank	A8-3	1. Fuel pump status	SD
9.2.6	Depressurize Cabin	D	1. Verify cabin pressurization system in ground mode	A3-2	1. Cabin pressurization mode	SD
9.2.7	Neutralize Stabilizer Trim	D	1. Run stabilizer trim to neutral position	A5-3	1. Stabilizer trim position	CSPD
9.2.8	Perform After Landing Checklist	--	1. Select after landing checklist 2. Read checklist challenge 3. Respond to challenge	A4-2 A4-2	1. Checklist items 2. Items completed 3. Recall of remaining items	MFD MFD MFD
9.3	PARK AIRPLANE					
9.3.1	Taxi to Gate	D	1. Turn on appropriate runway turn off light		1. Turn off light switch position	

Table E-1. Crew Procedural Functions (page 50 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
			2. Maintain directional control using nose wheel steering 3. Maintain speed control using brakes 4. Turn off runway turn off and taxi lights 5. Follow taxi signalman's directions 6. Apply brakes to stop in parking position		2. Taxi light switch position 3. Hydraulic brake pressure	
9.3.2	Set Parking Brake	--	1. Hold pressure on brake pedals 2. Pull parking brake lever 3. Release pressure on brake pedals 4. Monitor for proper indications of brake set	A12 A5-1 A12 --	1. Hydraulic brake pressure 2. Parking brake position	SD A5-1
9.3.3	Extinguish Seat Belt Warning	D	1. Turn off fasten seat belt lights	A8-3	1. Fasten seat belt switch position	A8-3
9.3.4	Shut Off Windshield Wipers	D	1. Turn off windshield wipers (may be done sooner if conditions permit)	A8-1	1. Windshield wipers switch position	A8-1
9.4	SHUT DOWN ENGINES					
9.4.1	Confirm Ready for Shutdown	--	1. Verify first officer has complete preparations for engine shutdown	Verbal	1. Verbal response	--

Table E-1. Crew Procedural Functions (Page 51 of 53)

Function Number	Function Name	Criti-cality	Crew Action	Control Location	Information Requirements	Display Location
9.4.2	Shut off Engines	--	1. Shut off fuel and ignition to both engines 2. Monitor engine instruments for shutdown			
9.4.3	Shut off Hydraulic Pumps	--	1. Turn off electric-driven pumps 2. Turn off air-turbine driven pump	A8-3 A8-3	1. Electric-driven hydraulic pump switch position 2. Air-turbine-driven hydraulic pump switch position	A8-3 A8-3
9.4.4	Shut off Emergency Exit Lights	--	1. Turn off emergency exit lights	A8-3	1. Emergency exit light switch position	A8-3
10.0	<u>POSTFLIGHT</u>					
10.1	PERFORM POST-SHUT-DOWN OPERATIONS					
10.1.1	Authorize Cabin Doors Open	--	1. Set cabin interphone control panel 2. Transmit "doors open" command to flight attendants	A10-1 Verbal	1. Attendant station to be called 2. Attendant ready for message	A10-1 CNSP
10.1.2	Adjust Seating	--	1. Release and remove seat belts	Seat	1. None	--

Table E-1. Crew Procedural Functions (Page 52 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
			2. Adjust seats as desired	Seat		
10.1.3	Set Cockpit Lights		1. Turn off beacon 2. Turn on dome light 3. Turn off compass and map light if not required 4. Turn off panel lights 5. Turn off circuit breaker panel lights	A8-3 A8-3 A7-3 A7-3 A8-3	1. Beacon switch position 2. Dome light switch position 3. Compass and map light switch position 4. Panel light switch position 5. Circuit breaker panel lights switch position	A8-3 A8-3 A7-3 A7-3 A8-3
10.1.4	Shut Down Flight and Navigation Equipment	C	1. Select avionics systems on multi-function display 2. Shut off systems either individually or as a group	A4-2 A4-2	1. Flight and navigation equipment "off"	MFD
10.1.5	Release Parking Brake	D	1. Verify wheel chocks in place 2. Release parking brake handle	Verbal A5-1	1. Parking brake released	A5-1 AAS
10.1.6	Shut Down Fuel Systems	D	1. Turn off fuel pumps 2. Close crossfeed valve	A3-2 A3-2	1. Fuel pump on/off state 2. Crossfeed valve position	SD SD
10.1.7	Shut off Crew Oxygen	D	1. Turn off all oxygen supply switches 2. Leave oxygen switch in 100% position	A10-1 A11-1 A10-1 A11-1	1. Oxygen supply switch position 2. Oxygen switch position	A10-1 A11-1 A10-1 A11-1
10.1.8	Perform Shutdown Checklist	--	1. Select shutdown checklist	A4-2	1. Checklist items 2. Items completed	MFD MFD

Table E-1. Crew Procedural Functions (Page 53 of 53)

Function Number	Function Name	Criticality	Crew Action	Control Location	Information Requirements	Display Location
			2. Read checklist challenge 3. Respond to challenge	A4-2 Verbal A4-2	3. Recall of remaining items	MFD
10.2	SECURE AIRPLANE					
10.2.1	Secure Air-Conditioning System	--	1. Close pack valve controls 2. Turn off gasper air	A3-2 A3-2	1. Pack valve position 2. Gasper air on/off state	SD SD
10.2.2	Set Electrical System	D	1. Observe external power available 2. Tie external power to main buses 3. Verify APU generator switches open	A3-2 A3-2 A3-2	1. External power available 2. Generator switch positions	SD SD
10.2.3	Shut Down APU	D	1. Turn off APU switch	A8-3	1. APU on/off state	A8-3
10.2.4	Secure Battery	D	1. Turn off battery switch	A8-3	1. Turn battery on/off state	A8-3
10.2.5	Perform Secure Checklist	--	1. Read checklist challenge 2. Respond to challenge	Verbal Verbal	1. Checklist items	Aural

Page

APPENDIX F: DETAILED RECOMMENDATIONS FOR SIMULATION MECHANIZATION

The flight deck systems, flight characteristics, and operating environment for the 1990s Active Controls Technology (ACT) airplane should be simulated in accordance with the systems and data described in this appendix.

F.1.0 FLIGHT CONTROLS AND OTHER CONTROLS

The cockpit simulator should provide manipulative controls, with control force loading where appropriate, for the following simulated functions:

- ACT controls
- Autopilot and flight director system
- Primary attitude
- Speedbrakes and spoilers
- Thrust
- Thrust reverser
- Automatic throttle
- Landing gear and brake system
- Flaps
- Trim

These function controls are discussed in the following paragraphs.

ACT Controls—Simulation of active controls should provide control loading to reproduce control forces experienced by the pilot under all flying conditions in combination with degraded modes of ACT. Controls located on the overhead panel are provided to disconnect the individual ACT functions. Simulation of the mechanical and electrical system test should be provided.

Autopilot and Flight Director System—The autopilot and flight director system computer program should simulate a multichannel fail-operational autopilot with full Category III autoland capabilities, including rollout. All transfer functions, logical switching, command rates, and angular limits should be simulated to ensure system performance under both normal and malfunction conditions.

Primary Attitude Controls—A control loading system should be provided to reproduce the control forces experienced by the pilot under all flying conditions. The design should provide flexibility, thereby enabling changes in force characteristics.

Rudder pedals should incorporate the normal adjustment found in airplanes. Pilot and copilot controls should be interconnected so that either pilot may control the simulator. The loads felt by the pilot and copilot should include simulation of the flight parameters pertaining at that time.

Speedbrakes and Spoilers—These surfaces should be simulated to respond to the associated speedbrake and lateral controls. Rate of movement and degree of opening should be functions of hydraulic pressure and aerodynamic force on the surface.

The automatic speedbrake system should be simulated fully to provide automatic extension of speedbrakes on touchdown and retraction for go-around after touchdown.

Flaps and Leading-Edge Devices—The flap system should be simulated. Leading-edge devices should be correctly scheduled as a function of trailing-edge position.

Trim—Stabilizer, elevator, rudder, and aileron trim should be provided.

Thrust Levers—A thrust lever module should be implemented to provide a constant control force over the complete range of lever movement, simulating the normal operating friction force.

Landing Gear—The correct relationship between gear and door warning lights, gear operation, and hydraulic pressure indication should be simulated. Their operation should be dependent upon availability of the appropriate simulated electric and hydraulic power supplies.

The operating rates of the landing gear actuators should be a function of hydraulic supply capability. Operation of the landing gear should be reflected in the hydraulic pressure readings.

The simulation should include operation of a complete alternate extension system. Interlocks that inhibit landing gear retract selection, such as truck tilt, body gear centering, etc., should be simulated. All logic circuits (primary and alternate) concerned with control and advisory functions for the landing gear and landing gear tilt functions should be simulated.

Wheel Brakes—The wheel brake system (covering brake source and brake application pressures, antiskid protection, and brake temperature monitor) should be simulated.

Brake accumulator charging rates and depletions with brake application should correctly reflect the capacity of the accumulator. Normal mode brake application pressures should be simulated as a function of pedal deflection and magnitude of brake accumulator pressure. Differential application of braking should be possible. Parking and autobraking functions should be integrated into the normal mode simulation. Brake low-pressure warnings should correctly relate to pressures in the hydraulic system selected as brake source. The antiskid simulation should cover inflight arming, locked-wheel protection, test circuits, failure monitoring, etc.

All control functions and indications should be simulated for a typical autobrake system. When the system is armed, the brakes should be applied automatically at the preselected deceleration level. Override of the autobrake system, caused by manual application of brakes or application of takeoff thrust, should be simulated.

A brake temperature monitor should be simulated, as brake temperatures achieved during the landing run depend upon the energy absorbed. Automatic warning of a brake overheat condition should be given if overheat temperatures are achieved.

Nose-Wheel Steering—The effects of hydraulic power supply availability, castering forces, and rudder pedal interconnect should be simulated. Response rates of the nose-wheel tillers should be typical of a commercial transport aircraft. All logic associated with body gear steering pressure, steering unlocked, and steering-not-centered annunciators should be simulated.

F.2.0 ADVANCED CONTROLS AND DISPLAYS

The term "controls and displays" includes all electronic displays, controls, and keyboards located in the cockpit.

F.2.1 ELECTRONIC DISPLAYS

The electronic displays include two categories:

- Those capable of displaying graphics
- Those capable of displaying only alphanumerics

F.2.1.1 HIGH-RESOLUTION PRIMARY (GRAPHICS) DISPLAYS

The flight deck should have a total of nine high-resolution primary displays with quality graphics capability to simulate advanced display concepts. The following concepts will be investigated:

- Electronic attitude director indicator (EADI)
- Electronic horizontal situation indicator (EHSI)
- Engine display (ED)
- System display (SD)
- Head-up display (HUD)

Except for the HUD, all of these displays require a minimum of four colors (red, orange, yellow, and green) to present the information. The HUD requires a monochromatic presentation device for the 1985 time period and possibly a multicolor device for a later period.

The EADI, EHSI, ED, and SD should be the same size for commonality and should be usable with the major dimension, oriented either horizontally or vertically.

The following paragraphs contain functional descriptions of the types of data and formats for the EADI, EHSI, ED, SD, and HUD.

EADI–The EADI displays vehicle attitude, velocity orientation, energy managemen information, and flight director commands based on signals received from an inertia navigation system (INS) or flight management computer and sensor. Figure F-1 shows a typical full-scale EADI format.

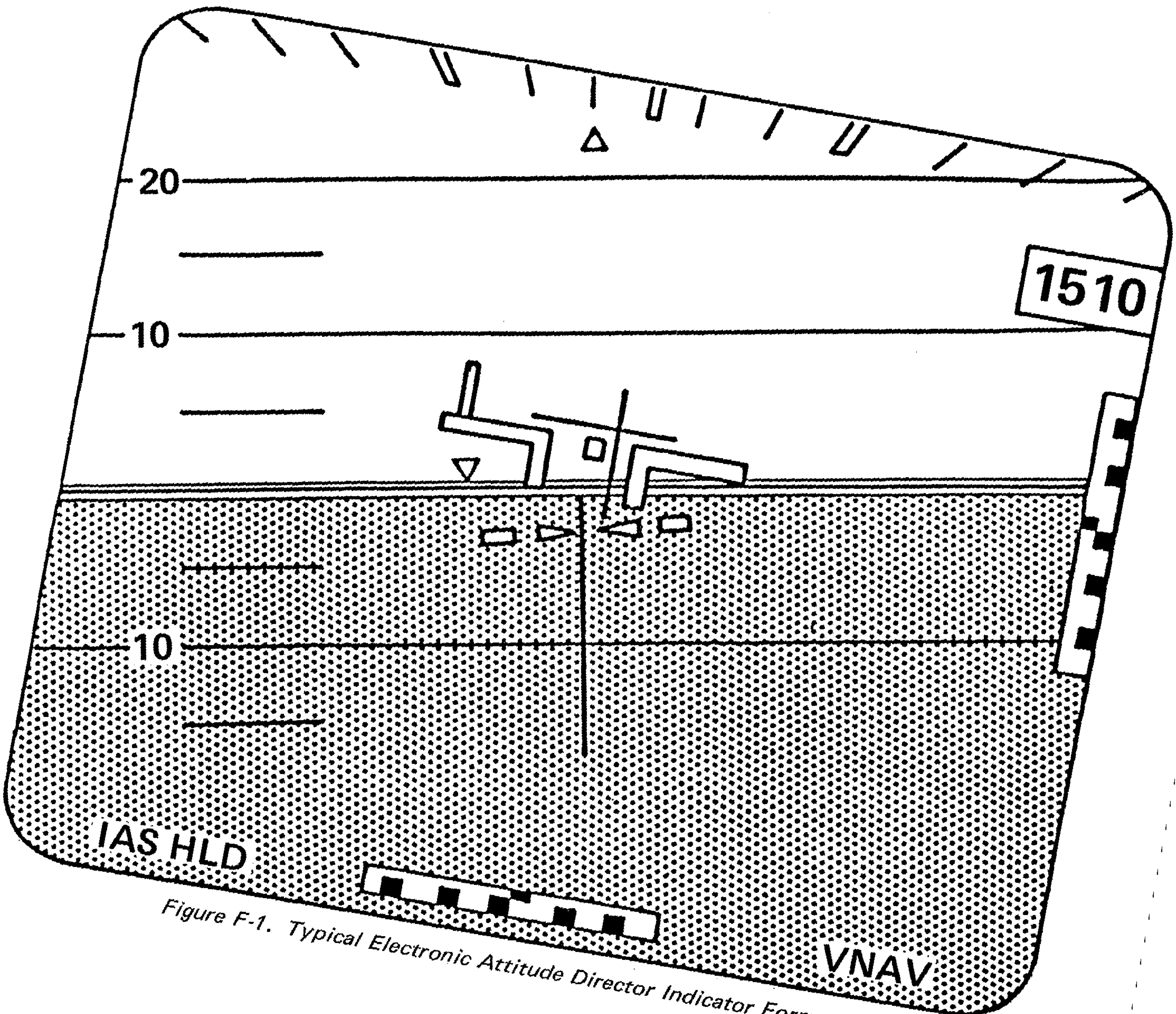


Figure F-1. Typical Electronic Attitude Director Indicator Format

EHSI—The EHSI displays standard horizontal situation indicator (HSI) functions, plus mapping, weather radar with a modified iso-echo contour, alphanumerics, and performance data. The EHSI requires a four-color presentation device, and it should be possible to designate any one of the four colors to a specific symbol. Figure F-2 shows a typical format.

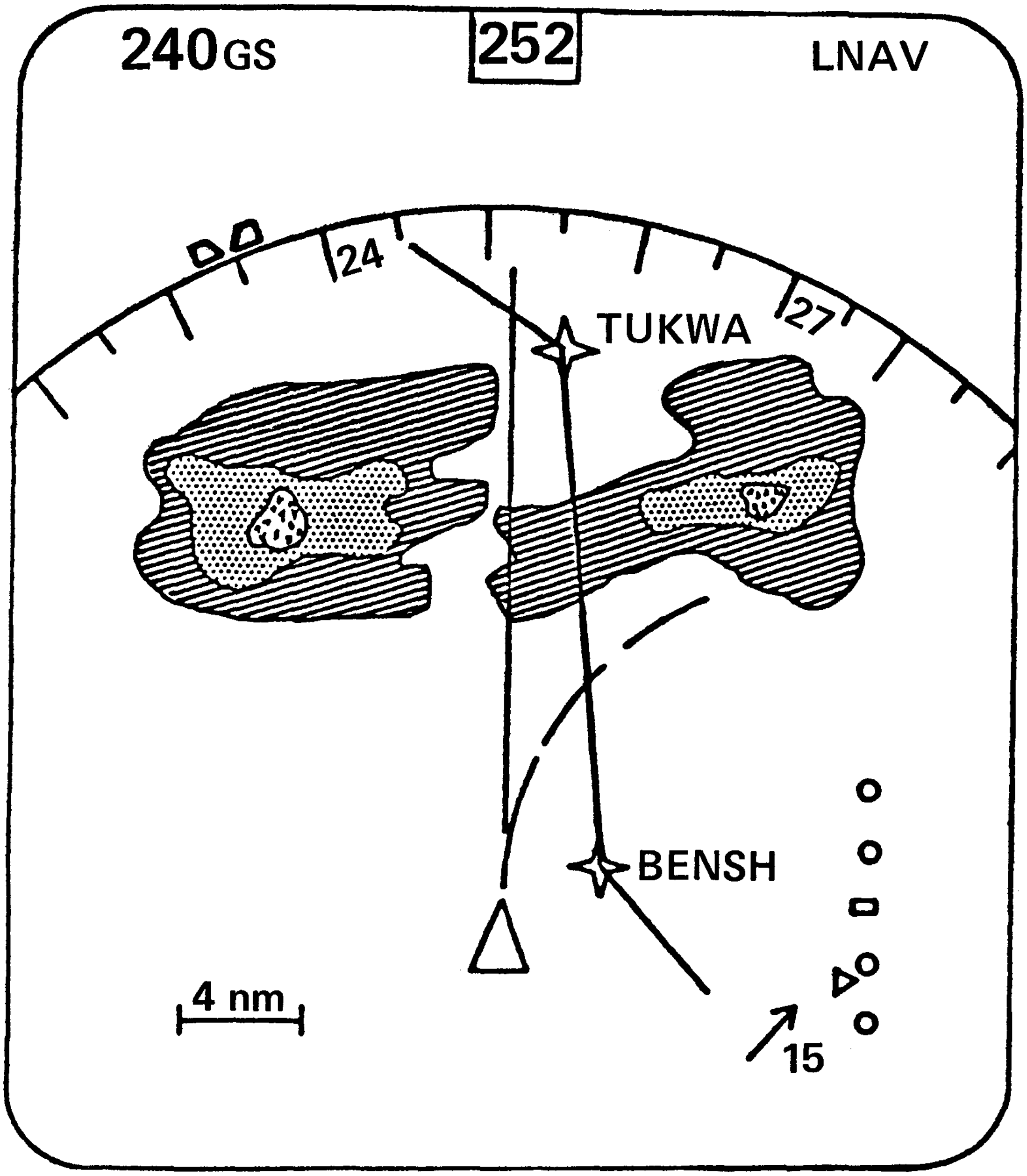


Figure F-2. Typical Electronic Horizontal Situation Indicator Format

ED and SD–The ED and SD are used primarily for monitoring engine and system status, respectively; however, they can be used to display normal EADI or EHSI functions, if necessary. Formats for engine and systems data are to be determined (TBD).

HUD–HUD data are generated on a small, high-resolution display device and projected onto a see-through lens in front of the pilots' eyes. Data content on a HUD should be identical to that of the EADI. Figure F-3 shows a typical HUD format.

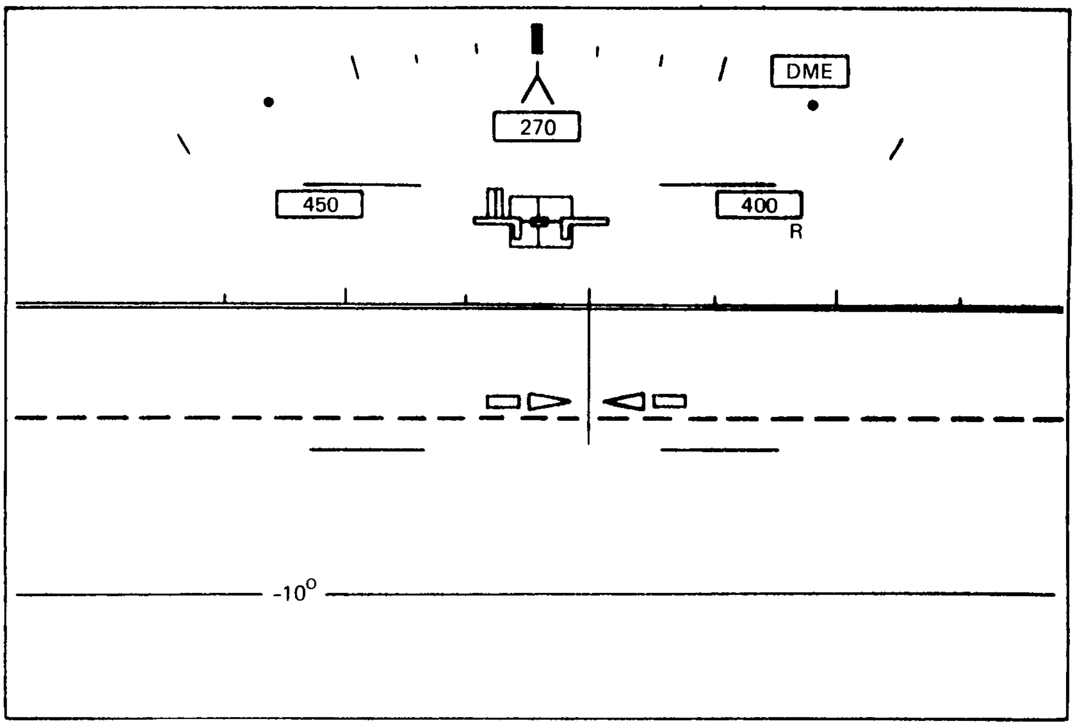


Figure F-3. Typical Head-up Display Format

F.2.1.2 LOW-RESOLUTION ALPHANUMERIC DISPLAYS

The flight deck should have twelve alphanumeric displays: six for secondary flight instruments, two for warning and caution data, one for communication and navigation status, and three for the multifunction keyboard (MFK) verification readouts. Whenever the MFK readout displays are not being used for program verification, the basic format on the pilot's display should be navigation data and on the first officer's display should be communication data. The size, shape, color, and resolution of all alphanumeric displays should be identical. Resolution for these displays is a minimum of 13 pixels/cm (33 pixels/in).

F.2.2 MULTIFUNCTION KEYBOARD

The requirement for controlling many functions by a single device is best handled by an MFK. For a keyboard type of input system, this may be accomplished by using multiple-legend keys that display a legend appropriate to the current function of the key and change both legend and function when their present configuration is no longer required. This concept enables a relatively small keyboard of 16 to 24 switches to perform the functions of much larger or more numerous keyboards by presenting only pertinent information and input options at any given time. Three of these MFKs are required within the cab, one for each crew member and one for the test conductor. Voice system supplement may be used.

F.3.0 AIRPLANE SYSTEMS

F.4.0 COMMUNICATION AND NAVIGATION SYSTEMS

F.5.0 TEST CONDUCTOR CONTROL STATION–PRIMARY

F.3.0 AIRPLANE SYSTEMS

F.3.1 HYDRAULIC SYSTEM

The functioning of all controls and components of the hydraulic system, such as check or relief valves, shutoff or depressurizing valves, flap priority valves, accumulators, etc., should be simulated.

The following fluid-quantity-related features of a typical airplane hydraulic system should be simulated:

- Exchange volume of accumulators and actuators where such exchange is significant (e.g., landing gear and brakes)

- Loss of fluid due to system failure (e.g., a ruptured pipe)

- Level of reservoir fluid at which low-quantity warning should be given

- Fluid temperature at which an overheat warning should be indicated

- Fluid quantity test

The following typical airplane hydraulic system fluid-pressure-related characteristics and features should be simulated:

- Pressure transients as a function of using the hydraulic system
- Pump load effects on the engine electrical-generating and pneumatic systems
- The pressure decay rates that occur when depressurizing the pumps
- Low-pressure warnings

F.3.2 PRIMARY ELECTRIC SYSTEM

The ac and dc electric systems should be simulated to the extent required for appropriate indication of the following faults:

- Overexcitation and overvoltage
- Underexcitation and undervoltage
- Difference current
- Open phase
- Differential fault
- Overspeed
- Underspeed
- Overcurrent

Where the load difference indication for specific equipment is particularly important, the difference should be simulated.

The constant-speed-drive (CSD) oil pressure and temperature indications should be representative of a typical airplane under normal and abnormal operative conditions. Oil temperature readings should properly reflect flight profile, engine settings, generator load, and CSD disconnect.

All control logic of the generators and bus bar distribution, including split system operation, should be simulated.

F.3.3 AUXILIARY POWER UNIT

Start—Auxiliary power unit (APU) start and operation should be dependent on availability of fuel. Starting sequence and acceleration to governed speed should demonstrate typical airplane characteristics.

Control—Control of the APU should be simulated such that variations in electric or pneumatic offtakes will produce corresponding changes in revolutions per minute (RPM) and exhaust gas temperature (EGT).

Performance—The effects of APU performance on other systems should be computed with respect to ambient conditions and power offtakes. APU performance parameters should be computed such that the effects of overload are displayed.

F.3.4 PROPULSION

Start—Engine cranking and starting characteristics should be simulated. Effects on the engine start characteristics due to the starter failing or dropping out prematurely (caused by duct pressure loss or starter or logic failure) should be simulated. When ignition is selected correctly and engine speed has reached the appropriate RPM, application of fuel should cause the engine to light. Transient EGT, fuel flow, and RPM characteristics should be reproduced as the engine accelerates and stabilizes at idle speed.

Engine Control—The relationship between the simulated engine and the pilot's power lever and start lever movement should be analogous to a typical airplane engine.

Engine Performance—The relationship between the engine parameters (RPM, thrust, EGT, etc.) and all atmospheric conditions within the flight envelope, bleed air offtake, mechanical load to electric generators and hydraulic pumps, and compressor offloading and intake should be simulated.

Reverse Thrust—Control of the thrust reversers, including operation of mechanical interlocks on power lever movement, and indication of thrust reverser status should be simulated.

Windmill RPM—When an engine is "flamed out" in flight, the simulated engine should realistically run down and stabilize at a shaft speed appropriate for the ambient conditions and airspeed.

Engine Oil System—The characteristics of an engine oil system should be simulated. Oil quantity should be initialized by the test conductor and depleted at a realistic rate while the engine is operating. The effects on oil quantity due to oil circulation should also be simulated. Transient and steady-state oil pressure readings should be related to RPM, oil quantity, and simulated oil temperature.

Oil temperature should be related to engine RPM, oil quantity, fuel flow, fuel temperature, and ambient conditions. During and after engine shutdown, indicated oil temperature should decay to ambient. The effect of the fuel heater upon fuel and oil temperatures also should be simulated.

EPR–EPR should be related to power lever position, altitude, outside air temperature, engine bleed air consumption, and forward speed.

RPM–Each compressor RPM also should be related to engine pressure ratio (EPR), altitude, outside air temperature, engine bleed air consumption, and forward speed.

EGT–The computed indications of EGT should be correctly related to EPR, altitude, outside air temperature, engine bleed air consumption, and forward speed together with any surges apparent during starting, accelerating, or fault conditions. During and after engine shutdown, indicated EGT should decay to ambient.

Fuel Flow–Fuel flow should be related to power lever position, engine speed, and compressor delivery pressure.

Vibration–Typical transient and steady-state engine vibration indications should be simulated.

Thrust–Total engine thrust should be related to EPR, Mach, and ambient conditions.

F.3.5 FUEL SYSTEM

The fuel system instruments and indications should simulate the characteristics of a typical airplane under conditions of direct tank-to-engine feed, crossfeed, and intertank transfer.

Operation of fuel system controls should produce appropriate steady-state and transient indication as described in the following paragraphs.

Fuel Flow–Fuel flow should be computed for all pipes in the engine feed system, including crossfeed and transfer pipes, to produce correct depletion rates and pressure indications.

Each flow should respond to all associated controls, boost pump operation, and engine demands.

Fuel Pressure—Pressures in the fuel system should be computed from tank flow rates and reflect boost pump performance or gravity feeding under all flight conditions. When operating under conditions of low fuel level in any tank, fuel movement as a function of body attitude and acceleration should be simulated.

Fuel Transfer—Gravity transfer of fuel between tanks should be dependent on simulated airplane attitude, tank quantities, and valve states. Fuel system simulation should allow for transfer of fuel between main tanks under conditions of boost pumps failed.

Fuel Quantity—The fuel flow to and from each tank should be computed and integrated with respect to time to produce individual tank contents. Quantity readouts should also be appropriate for transients related to airplane acceleration and deceleration and body attitude.

Fuel Dumping—Operation of the fuel dump controls should be simulated. The effects of fuel dumping should be such that individual tank jettison rates will vary according to the total number of tanks jettisoning fuel and number of jettison nozzles selected open.

Fuel Temperature—Engine fuel inlet temperature should depend upon engine oil temperature, tank temperature, and fuel heater operation. Fuel tank temperature indication should follow the ambient temperature at a rate dependent upon the thermal capacity of the fuel.

Control Valves—The operating characteristics of the airplane fuel control valves and associated indicators should be reproduced, including the effects of removing power in transit.

F.3.6 CABIN PRESSURIZATION

The following indicated control and display effects of the cabin pressurization system should be simulated:

- Automatic pressure control, including landing field selection, rate-of-change limit, and flight altitude

- Semiautomatic pressure control characteristics, including rate selection, isobaric selection, maximum differential pressure control, and barometric correction of their effects on outflow valves and cabin pressure indications

- Standby pressure control with appropriate effects on outflow valves and cabin pressure indications

- Manual pressure control with appropriate effects on outflow valves and cabin pressure indications

- Cabin altitude, differential pressure, and rate-of-climb indications as a function of mode of control, airplane altitude, airflow available to the pressurized areas, status of outflow valves, safety valves, and other leakage areas

F.3.7 PNEUMATIC SYSTEM

The following characteristics of the pneumatic system should be simulated:

- Values of bleed airflows taken from each supply stage of each engine; the resulting effects should be shown on engine instruments

- Mixing the high- and low-pressure bleed air and the resulting effect on pneumatic duct pressure and temperature

- Effects on duct pressures and airflows of any pressure regulation of flow controllers; duct pressure losses due to airflow should be simulated

- Effect on duct temperatures of the performance of any bleed precoolers present

- Heat loss and gain effects on duct temperature due to outside ambient air temperature

- Duct pressure drops due to engine starting

- Ground-air cart delivery pressure and temperature

- APU air delivery pressure and temperature

- High- and low-pressure and temperature warnings and automatic system shutdowns

- Pressure and temperature at entry to the thermal anti-ice system and the air-conditioning and pressurization system

The functioning of all controls and components in the pneumatic system such as flow control valves, bleed valves, etc., should be simulated.

F.3.8 ICE PROTECTION, DEFOGGING, AND RAIN REMOVAL

The wing ice protection system should be simulated, including cycling effects and malfunction indications. Ground anti-ice checkout facilities, including overheat conditions, should be simulated. The appropriate bleed effects should be indicated. The following systems and effects should be simulated:

- Pitot-static system icing
- Engine anti-ice system controls and indications
- Windshield anti-ice, pitot heaters, and defogging indicators and controls
- Rain removal and repellent system

F.3.9 FIRE DETECTION AND EXTINGUISHING

All control and indicator functions for the engine, nacelles, and APU fire detection and extinguishing systems and for the cargo smoke detection system should be simulated. This should include all-loop fire and fault test and squib test features.

The nacelle temperature indicator readings should correctly relate to existing operating conditions (i.e., NORMAL, OVERHEAT, FIRE).

Operation of the engine fire switches should correctly affect systems.

Malfunctions that activate the warnings and require extinguishing action should be simulated.

F.3.10 CENTRAL AIR DATA SYSTEM

Simulation of a central air data system should be provided. This system should be fully simulated to ensure that any failure, such as a blocked pitot, manifests itself realistically at all times.

F.3.11 AIRCREW ALERTING SYSTEM

The aircrew alerting system simulation should indicate the following categories of conditions:

- Warning—Emergency, operational, or airplane system conditions that require immediate corrective or compensatory action by the crew

- Caution—Abnormal operational or airplane system conditions that require immediate crew awareness and eventual corrective or compensatory crew action

- Advisory—Operational or airplane system conditions that require crew awareness and may require crew action

- Information—Operational or airplane system conditions that require cockpit indication but not necessarily as part of the integrated warning system

F.3.12 LIGHTING

The following lighting functions should be simulated:

- Interior lighting
  - Storm
  - Dome
  - Main panel (background, legend)
  - Overhead (background, legend)

- Exterior lighting
  - Runway turnoff
  - Landing
  - Navigation
  - Beacon

F.3.13 SIMULATED AURAL WARNINGS

The functions, tone characteristics, and speaker locations for all aural warning devices should correspond to those of a typical airplane installation.

Types of aural warnings to be simulated are as follows:

- Fire bell
- Stall–clacker
- Overrotation on takeoff–horn
- Unsafe takeoff configuration–horn
- Excess operating airspeed–clacker
- Autopilot disengage–wailer
- Landing gear not down and locked–horn
- Excess cabin altitude–horn
- Center stick controller shaker–clacker
- Ground proximity warning–wailer and voice

Guidelines from advanced caution and warning system studies should be used for guidance regarding an integrated caution and warning approach.

F.4.0 COMMUNICATION AND NAVIGATION SYSTEMS

F.4.1 COMMUNICATION

F.4.1.1 HF COMMUNICATION

The functions of a two-channel high-frequency (HF) communication system should be simulated. Airplane-type control units should be used with the tuning tone and/or light simulated.

When either HF channel is transmitting, both receivers should be muted. Sidetone should be independent of receiver audio level control.

F.4.1.2 VHF COMMUNICATION

The functions of a three-channel very-high-frequency (VHF) communication system should be simulated.

F.4.2 NAVIGATION

F.4.2.1 RADIO NAVIGATION SYSTEMS

The selection and tuning of the following radio navigation systems should be fully simulated:

- VHF navigation (VOR–ILS and GS)
- Automatic direction finder (ADF)
- Marker system

The VHF navigation system simulation should incorporate a program to compute the cone of confusion. This module should simulate a realistic movement of the radio magnetic display (RMD) and flags in the cone of confusion area.

The audio signal strength should vary realistically with range. At more than maximum range, the audio signal should be inaudible.

F.4.2.2 NAVIGATION SYSTEMS

The following navigation systems should be simulated:

- Inertial reference systems (IRS)
- Magnetic heading reference system
- Attitude system(s)
- ADF
- Marker system
- Air traffic control (ATC) transponder
- Very-high-frequency omnidirectional range (VOR) and distance measuring equipment
- Microwave landing system (MLS)
- Omega
- Global positioning system (GPS)
- Loran-C
- System malfunctions

These systems are discussed in the following paragraphs.

Inertial Reference Systems—The functions of the battery unit and navigation unit, comprising the inertial platform and flight management computer, should be simulated. The primary functions of the control and display units should be selectable through the multifunction keyboard.

Magnetic Heading Reference System—The functions of a magnetic heading reference system and the standby magnetic compass should be simulated. The simulated flux valves should be correctly influenced by magnetic variation effects. The simulation should also approximate the turning errors and the east-west acceleration error.

Attitude System(s)—The primary attitude and the standby attitude systems should be simulated. The standby attitude indicator simulation should approximate the effects of toppling and erection when power is removed from, or restored to, the instrument.

ADF—The ADF system simulation should incorporate a program to compute the "station passage." This module should provide a realistic simulation of the RMD during "station passage."

Marker System—Simulation of the marker system should allow for operation of the visual and audio indications. Effects of the different thresholds for the visual and aural signals should be simulated. Reception of the markers should be suitably modified by the selected positions of the marker sensitivity control. The audio signal strength should vary realistically with range.

ATC Transponder—The ATC transponder should be simulated. Test functions for cockpit checks should be operable.

VOR and DME—The following functions of a two-channel distance measuring equipment (DME) system should be simulated:

- Warmup time
- Test and override functions
- Memory and strobe submodes

Microwave Landing System—(Onboard functions to be simulated—TBD.)

Omega—(Onboard functions to be simulated—TBD.)

GPS—(Onboard functions to be simulated—TBD.)

Loran-C—(Onboard functions to be simulated—TBD.)

System Malfunctions—Malfunctions applied from the test conductor's controls should result in the appropriate malfunction and action codes being displayed at the control display units (CDU), when selected. Correct remedial action by the crew should result in the malfunction being overcome.

Navigation drift errors in both latitude and longitude should be able to be introduced through the test conductor's console. Instantaneous position errors should also be capable of being introduced in both latitude and longitude.

F.5.0 TEST CONDUCTOR CONTROL STATION–PRIMARY

The primary test conductor station should be located so that the test conductor has visibility of the controls and instruments of all crew members and can observe crew reactions.

The test conductor's console should include the following functions:

- Test start, stop, and reset switches
- Track plots, approach plots, and readouts of selected parameter values
- Controls to initialize airspace, airfield, and external visual conditions (e.g., area of operation, runways, visibility, runway visual range, cloud ceiling, cloudtop, horizon brightness, ground fog, scud cloud, weather, horizon brightness, VASI, and pre-programmed airborne traffic situation)
- Controls to initialize atmospheric conditions
- Controls to initialize airplane position, airspeed, altitude, etc.
- Controls to introduce abnormal and emergency conditions
- Full audio system control
- Controls to lock or freeze specific functions
- Controls to record various aspects of the exercises, the recorded parameters forming the basis of postexercise debriefing
- Controls to reposition the airplane during the exercise to condense the overall exercise into an acceptable time-scale
- Record or replay last 5 min or so of testing or training exercises

- Emergency power shutdown of electric power, sound, and motion-base power

- Monitoring of system status and flight situation data; system status information includes such items as:

  - Systems activated
  - Sequencing information
  - Caution and warning
  - Parameter monitoring
  - Times and events

  Flight situation data would include primary flight instrument, engine performance, and fault analysis.

- Multifunction controls for communicating with the host computer

F.6.0 ENVIRONMENT AND AIRPLANE CHARACTERISTICS SIMULATION

F.7.0 BUDGETARY ESTIMATES FOR RECOMMENDED MECHANIZATION OF THE SIMULATION

F.6.0 ENVIRONMENT AND AIRPLANE CHARACTERISTICS SIMULATION

The simulator should be capable of providing realistic conditions of flight environment and consequent effects on airplane characteristics in the categories described in the following subsections.

F.6.1 AIRFIELD ENVIRONMENT

Simulation of airfield environmental conditions applicable to both takeoff and approach and landing phases of flight should include:

- Barometric Pressure–Sea level pressure, variable from 800 to 1200 mbar (24 to 35 inHg).
- Airfield Pressure–Variable over a range equivalent to the preceding.
- Sea Level Temperature–Variable from -35°C (-30°F) to +65°C (+150°F).
- Outside Air Temperature–Variable through a range to +100°C (+212°F).
- Windspeed–Variable from 0 to 129 m/s (0 to 250 kn). Windspeed changes selected during flight will not cause upsets to the simulated airplane.
- Wind Direction–Variable through 360 deg. Changes of wind direction selected during flight will not cause upsets to the simulated airplane.
- Runway Type–Selected to represent a smooth or rough runway.
- Runway Conditions–Will be selected to represent any of the following conditions in conjunction with the runway type selected:
  - Dry.
  - Wet–Appropriate to a runway having sufficient standing water to induce aquaplaning.

- Slush–Appropriate depth to cause severe performance deterioration in takeoff and landing.

- Ice–Runway covered by ice.

- Ice Patches–Runway basically wet, with patches of ice, random in size and distribution, so as to affect each main gear in turn.

F.6.2 INFLIGHT ATMOSPHERIC ENVIRONMENT

Simulation of atmospheric environmental conditions applicable to all phases of flight should include:

- Temperature Change Rate per 300m (1000 ft)–Variable between -6°C (-21°F) per 300m (1000 ft) and +1°C (+34°F) per 300m (1000 ft) at 0.6°C (+33°F) per 300-m/s (1000-ft/s) maximum.

- Wind Profile–It should be possible to select at least three separate wind profiles. These profiles should be superimposed on the set windspeed and direction parameters.

- Wind Shear–It should be possible for the test conductor to select from at least the 10 different thunderstorm and wind shear models currently defined for wind shear studies by the FAA. The test conductor should also have the capability to position the shear model in either the takeoff or touchdown zones of any airport.

- Turbulence–It should be possible to select any of the following four types of atmospheric turbulence: cobblestone, rough air, severe turbulence, and jet upset. The intensity should be controllable by the test conductor.

- Icing–It should be possible to vary the severity of icing to affect the engines, airframe, and pitot heads when the total air temperature falls below 0°C (+32°F).

- Atmospheric Condition Reset–It should be possible to instantaneously reset atmospheric pressure and temperature to standard ICAO standard atmosphere (ISA) values of 1013.2 mbar (29.92 inHg) and +15°C (+59°F) at mean sea level. Similarly, it should be possible to set the windspeed, wind direction, and turbulence level to zero.

F.6.3 NAVIGATION ENVIRONMENT

The following types of ground-to-air stations should be simulated:

- Nondirectional beacon (NDB)
- Very-high-frequency omnidirectional range (VOR)
- Distance measuring equipment (DME)
- Instrument landing system (ILS)
- Microwave landing system (MLS)
- Landing markers
- Airways markers
- Omega and Loran-C
- Global positioning system (GPS)

F.6.4 EXTERNAL VISUAL ENVIRONMENT

The simulator should provide a day or night visual scene for both pilot and copilot. Specific day, night, and dusk data bases (airfields) should be preprogrammed.

Surfaces should be displayed to represent runway, taxiing, and parking ramp markings as illuminated by airplane landing lights, presenting smooth intensity gradation for realistic fading. The markings should be illuminated as coplanar solid surfaces of true perspective. Surfaces should also be displayed to represent the geographical features of the airfield and the local operating area such as prominent hills, rivers, and typical terrain colorations.

F.6.5 SOUND ENVIRONMENT

Simulation of airplane sounds should be realistic to the degree that the direction as well as the type and intensity are presented. Sound simulation should be automatic and include, but not be limited to, the following noises commonly audible in the cockpit:

- Ground power carts (electric and air)

- Powerplants (engine whine, engine efflux roar, air noise, and thrust reverser operation)

- Aerodynamic noise
- Compressor stall
- Equipment cooling
- Landing gear lock
- Wheel rumble
- Landing impact
- Buffet–landing gear, spoilers, and stall
- Main oleo extension
- Cabin background sound
- Air-conditioning airflow
- Runway effects (rumble)
- Relay and other cockpit equipment background noise

The sequence, intensity, and pitch should vary to reflect changes in operating conditions.

F.6.6 GROUND HANDLING CHARACTERISTICS

The behavior of the airplane in normal and abnormal handling conditions on the ground should be simulated. Brake pressure, speed, wheel load, tire slip angle, tire self-alignment torque, and friction coefficients should be considered when calculating the landing gear forces and moments. The simulation should include the correct effects of nose-wheel steering, differential braking, asymmetric thrust, and body gear steering effects. Pushback should also be simulated.

Crosswind characteristics dependent on the onground aerodynamics of the airplane should be simulated. The simulator should display proper weathercock effect, correct transition between ground and air, and other handling characteristics with particular regard to roll tendency caused by a crosswind.

Various runway conditions ranging from rough and dry to ice covered should be simulated and controllable from the test conductor's station. The simulation should also include such effects as aquaplaning and skidding on ice. The effects of rough runway on airplane instruments should be simulated correctly.

F.6.7 GROUND-TO-AIR TRANSITION CHARACTERISTICS

Transition from ground to air and vice versa should be simulated with no discontinuities at any time. Aerodynamic effects of flying in ground effect (with crosswind as selected) should be portrayed accurately along with all the sounds, vibration, and motion cues. The crew should have all the sensory inputs normally used to assess touchdown performance.

F.6.8 AIRBORNE CHARACTERISTICS

The airborne handling and stability of an airplane are functions of its aerodynamic derivatives and mass-inertia properties, which should be simulated. The stability of the simulator and its dynamic performance should be correct throughout the flight envelope.

Figure F-4 shows the high- and low-speed flight envelopes for two gross weights, which represent extremes for flying qualities. The maximum design takeoff weight is about 122 500 kg (270 000 lb) (maximum design taxi weight is 122 900 kg (271 000 lb)); and the end-of-cruise, descent, and landing weights are about 90 700 kg (200 000 lb) (operational empty weight is 77 300 kg (170 560 lb)). The operational flight envelope is defined by V_{MO}/M_{MO}, $1.2V_S$, and a maximum altitude of 12 800m (42 000 ft). A design envelope for emergency flight is provided by V_D/M_D/flap placard and stall warning speeds. Therefore, simulation scenario constraints will be defined by the emergency flight envelope with high-speed limits of V_D = 221-m/s (430-kn) calibrated airspeed, flap placard = 118-m/s (230-kn) equivalent airspeed, and low speed of stall warning, which varies with weight. Normal conditions assume a maximum altitude of 12 800m (42 000 ft). Flight conditions that require restricted flight will be limited to 144-m/s (280-kn) calibrated airspeed, Mach = 0.76, and maximum altitude of 7600m (25 000 ft).

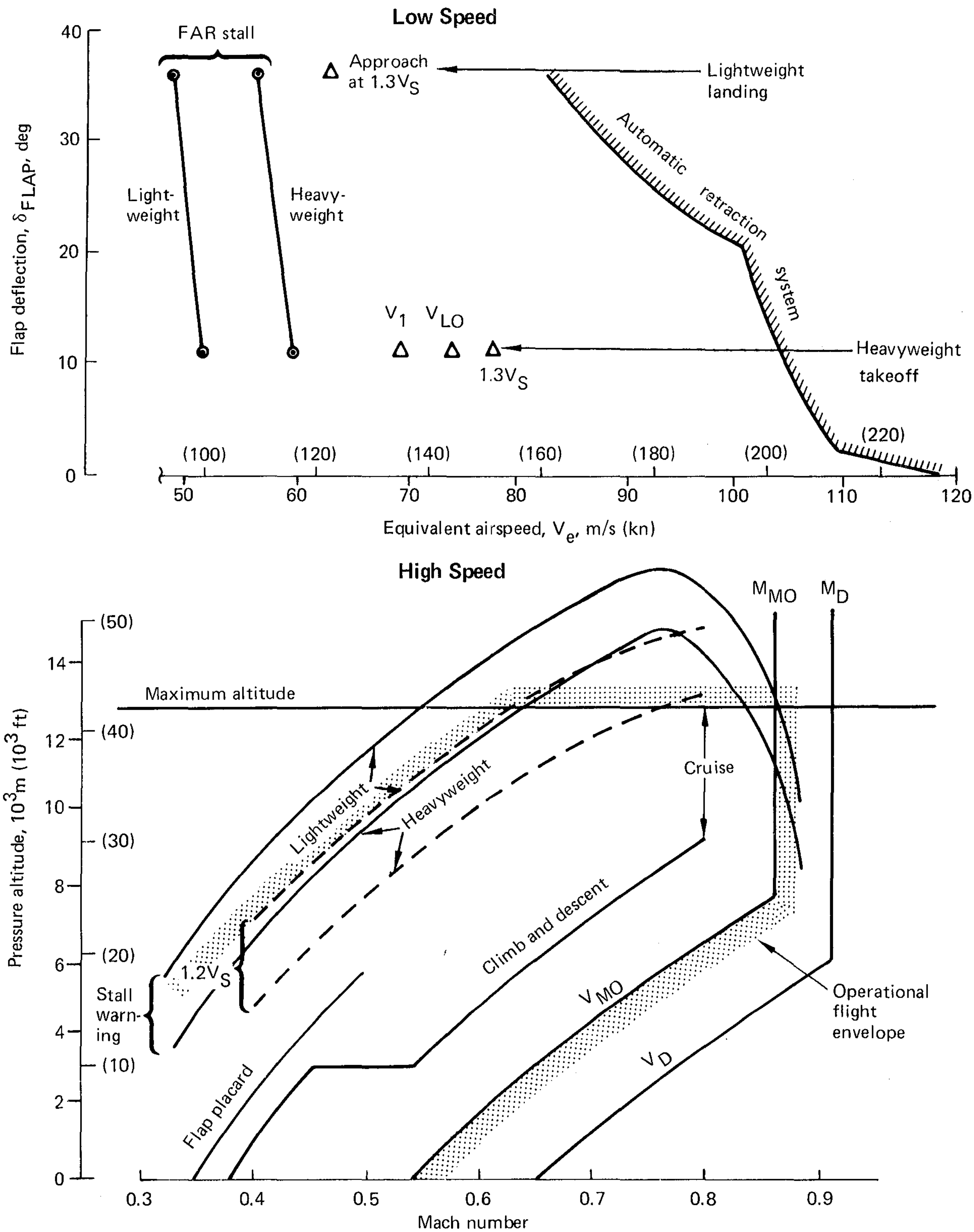


Figure F-4. Speed and Altitude Flight Envelopes

All prestall, stall, and poststall characteristics should be simulated. The buffet associated with the stall and high Mach number should be introduced through the motion system.

Power changes and changes to secondary controls, such as flaps, should affect the behavior of the simulator in a way that corresponds to a real airplane.

Instrument response and lag characteristics together with position error terms should be simulated. Instrument switching should be simulated where applicable.

Changes to weight, center of gravity, fuel load, and temperature should be accurately reflected in the performance of the simulator. Introduction of wind should result in a corresponding drift of the simulator over the ground and a change in ground speed. The presence of atmospheric turbulence should be displayed on the instruments and in the flying characteristics of the simulator. Representative cockpit transient movements should be introduced through the motion system. Introduction of airframe icing should result in changes to the weight, lift, and drag.

F.7.0 BUDGETARY ESTIMATES FOR RECOMMENDED MECHANIZATION OF THE SIMULATION

F.7.1 MECHANIZATION FEATURES

The simulation program will require a fixed-base configuration cab, with selected support from a motion-base engineering simulator cab with roll, pitch, and heave axes; an electrohydraulic force feel system; and a television visual system. The motion system cab should include cues for normal flight envelope ground rumble, touchdown, and engine-out for enhanced pilot recognition. Other features should include "live" flight deck turbulence and pitchup for takeoff rotation. A television visual system shows a runway with ground shading and tree-like projections that provide sink rate cues to the pilot. A masking feature should be available to simulate a ceiling on takeoff or a breakout condition on landing approach.

The simulation system would require control by a multiprocessor computer system (system refers to both hardware and software). The following tasks could then be supported simultaneously:

- Real-time simulation of airplanes with or without pilot in the loop
- Non-real-time simulations to evaluate various airplane trim conditions and fixed situations
- Program development and data preparation via multiple terminals
- Batch processing of simulation-related and general-purpose tasks
- Remote job entry to the computer data center

Peripheral devices available for the simulation program would typically include card reader, line printer, printer-plotter, multitrack magnetic tape, paper tape system, and disk storage.

It must be assumed that existing software for airplane independent software routines would be used, or the cost and time requirements would be prohibitive. Typical examples of such software routines are:

- Rigid-body equations of motion
- Generation of aerodynamic arguments
- Static atmospheric data

The 1990 ACT avionics and crew systems simulation would provide an all-electronic flight deck capability. The cab base should be readily accessible and be able to accept control loading modules that back-drive the flight controls. All instruments, switches, and annunciators would be functionally operational equipment or equivalent.

F.7.2 BUDGETARY ESTIMATES

The simulator cab facilities costs for development and fabrication are estimated at $2.5 to $3 million (exclusive of the simulation computers, visual, and force feel systems). These cost estimates are based on the budgetary estimates in Table F-1.

Table F-1. Engineering Budgetary Planning Estimates for Simulator Cab Buildup (Fixed-Base Cab)

Cost categories and items	Cost
• Labor • Mockup fabrication • Electronics interface • Engineering	$1 180 000
• Material (hardware) • Wiring (fiber optics) • Interfaces • Display processors • Symbol generators	842 000
• Black box equipment • Cab controls and displays (EADI, EHSI, etc.)	921 000
	Total $2 942 100*

Note: Estimate does not include pricing of simulation computers, visual systems, or force-feel systems.

*1981 dollars.

The handling qualities simulation, ACT avionics and crew systems simulation for resolution of design changes in controls and displays, software development of the task-dependent simulation routines, and the data analysis task are estimated to require between 30 to 40 man-years of engineering effort over a program period of 2 years.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-165963		

4. Title and Subtitle
INTEGRATED APPLICATION OF ACTIVE CONTROLS (IAAC) TECHNOLOGY TO AN ADVANCED SUBSONIC TRANSPORT PROJECT—ACT/CONTROL/GUIDANCE SYSTEM STUDY, VOLUME II—APPENDICES

5. Report Date
December 1982

6. Performing Organization Code

7. Author(s)
Boeing Commercial Airplane Company
Preliminary Design Department

8. Performing Organization Report No.
D6-51144

9. Performing Organization Name and Address
Boeing Commercial Airplane Company
P. O. Box 3707
Seattle, Washington 98124

10. Work Unit No.

11. Contract or Grant No.
NAS1-15325

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D. C. 20546

13. Type of Report and Period Covered
Contractor Report
Dec. 1980 to Jan. 1982

14. Sponsoring Agency Code

15. Supplementary Notes
Langley Technical Monitor: D. B. Middleton
Final Report

16. Abstract

This report documents the ACT/Control/Guidance System Task of the Integrated Application of Active Controls (IAAC) Technology Project within the NASA Energy Efficient Transport Program. The air traffic environment of navigation and air traffic control systems and procedures were extrapolated to the 1990s era for conclusions bearing on ACT airplane consequences of avionic system elements and operating procedures. A top-down approach to listing flight functions to be performed by systems and crew of an ACT-configured airplane of the 1990s, together with a determination of function criticalities to safety of flight, formed the basis of candidate integrated ACT/Control/Guidance System architecture.

In addition to the conventional control and navigation functions, the system mechanized five active control functions: pitch-augmented stability, angle-of-attack limiting, lateral/directional-augmented stability, gust-load alleviation, and maneuver-load control. The scope and requirements of a program for simulating the integrated ACT avionics and flight deck system, with pilot in the loop, were defined in terms of simulation scenario, system and crew interface elements to be simulated, and the recommended mechanization. Particular attention was given to the requirement to evaluate relationships between system design and crew roles and procedures.

17. Key Words (Suggested by Author(s))
Energy Efficient Transport, Active Controls Technology, ACT/Control/Guidance System, Pitch-Augmented Stability (Essential), Wing-Load Alleviation, Angle-of-Attack Limiting, Digital Autonomous Terminal Access Communication, Digital Data Bus

18. Distribution Statement
[redacted]

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	214	

Available: NASA's Industrial Applications Centers

N-305

End of Document